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THESIS

INVESTIGATIONS ON THE TEMPERATURE
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by

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Investigations on the Temperature Fluctuations and Incidence of Micro-thermals in the Air Adjacent to Natural Water Waves

by

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ABSTRACT

Temperature, wind (u and w), and wave data observed over Lake Michigan were analyzed to yield results on properties of sensible heat transfer in the near-surface layer. Significant features in the overwater data are associated with positive temperature fluctuations which appear as ramps (micro-thermals) in continuous traces. Objective methods based on the distinctive shape of the ramps were used to identify the occurrences of the micro-thermals. Although micro-thermals accounted for only about ten percent of the total record, they accounted for 32 percent of the total sensible heat flux. Results indicate that the occurrence and maintenance of the micro-thermals, and therefore, enhanced sensible heat flux are related to the presence of the waves. These results were obtained by considering Richardson numbers, significant wave height, and comparisons of wave and temperature traces. The Richardson number criteria for free convection do not appear to be the only determining parameters for the frequency of occurrence nor the development of the observed micro-thermals.

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β	Angle of Tilt of Micro-thermal from the Vertical
$H_{1/3}$	Significant wave height
$H_{1/10}$	Average Height of 1/10 highest waves
L	Monin-Obukhov length
N	Wave Field
R	Ratio of Heat Flux in Micro-thermals to that Outside of Micro-thermals
R_i	Richardson Number
R_c	Critical Richardson Number
s/s	Ratio of Skewness at a Point and Average Skewness
$S(\frac{dT}{dX})$	Skewness of the Downstream Derivative of the Temperature
T	Temperature
T_a	Air Temperature
T_s	Water Surface Temperature
U	Downstream Component of Velocity
U_T	Translation Velocity
W	Vertical Component of Velocity
Z/L	Stability Parameter

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I. INTRODUCTION

The atmosphere interacts with the earth's surface through the action of vertical fluxes inherent in the turbulent processes of the surface layer. These turbulent processes are responsible for the transfer of heat, moisture and momentum which in turn influence the basic state of the atmosphere. The same processes also determine those fluctuations influencing radio and light wave propagation. Present procedures for estimating turbulent fluxes of heat, moisture, and momentum in the surface layer of the atmosphere require additional direct information on the nature and extent of these processes.

Since it is impractical to measure these transfers, other than for experimental purposes, various methods have been chosen to estimate them. For example, exchange coefficients have been used to relate the fluxes of heat, moisture and momentum to the mean wind speed and the air-water temperature differences. Such an approach appears to be successful only for situations involving steady conditions without significant thermal stratification. Sheppard (1958) described the computation of momentum and heat transfer from measurements at two heights, assuming the exchange coefficients for heat and momentum are equivalent. This leads to an expression involving only the mean wind at some level and the air-water temperature difference if the structure of the surface layer is assumed.

In this study, features in the near water layer associated with vertical transfer of sensible heat are examined from detailed analyses of observational data. Furthermore, features are considered which cannot be associated with a fully turbulent regime. These data are from temperature, wind (u and w) and wave measurements over Lake Michigan which are analyzed with respect to the properties of both the temperature fluctuation and the sensible heat transfer. Measurements in the air were made at two levels at points along a plumb line directly above the wave gauge. The observations were made during times when the water was warmer than the air.

The most significant features in the overwater data appear to be associated with intense positive temperature fluctuations. These features appear as ramps in continuous traces as shown in the sample trace reproduced in Figure 1. The ramps appear simultaneously at the two measurement levels. Coincident velocity fluctuation vectors and wave traces are also reproduced in the figure.

Similar features have been observed in overland investigations wherein they were convincingly identified as plumes or micro-thermals (e.g., Webb, 1964). Furthermore, these phenomena have been described for horizontal scales ranging from meters to hundreds of meters, with apparently similar characteristics. These characteristics are:

1. well-defined vertical extent from below 1.5 meters to above 4.0 meters in this case;

2. associated upward motion; and

3. a tilt towards the downwind direction which can be determined by the time lag of the sharp drop in temperature (microfront) at the upwind edge between the two levels.

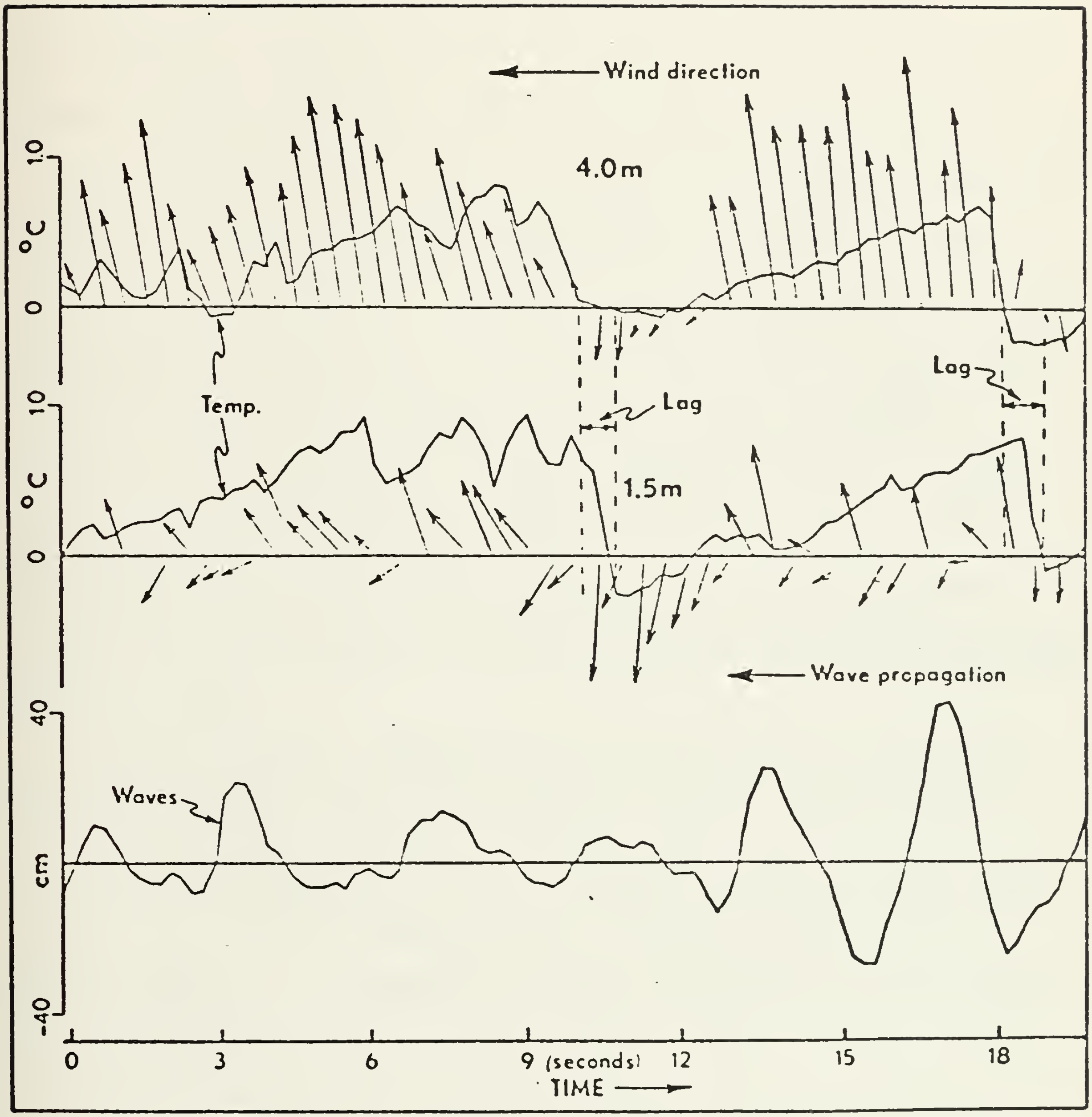


FIGURE 1. Sample of Temperature and Wave Height Traces and Velocity Fluctuations Associated with Micro-thermals Observed over Lake Michigan. Note Ramp Shape in Temperature Trace, Upward Motion in Velocity Vectors and Well-Defined Wave Height Extrema.

Solutions to several applied geophysical problems could be improved with a better description of the form and structure of the micro-thermals. For example, estimates of heat flux over the sea surface are often based on bulk aerodynamic transfer formulae with assumed exchange coefficients. These coefficients should account for the dynamics of the near water layer. Since it is in this layer that the micro-thermals obtain their identity, their influence on transfer processes should be considered when formulating or evaluating such coefficients. Predicting optical wave propagation is another area in which better descriptions of the micro-thermals and their occurrence are needed. A major factor affecting optical wave propagation is beam wander which is a function of density discontinuities along the path. This should certainly be related to the occurrence of micro-thermals, especially with respect to horizontal propagation in the near surface layer.

Several recent studies on the occurrence and properties of micro-thermals have been related to the prediction of optical wave propagation. Webb (1964) and Coulman and Hall (1967) provided an interpretation of such a role of the micro-thermals. A schematic example of their interpretation is shown in Figure 2.

The following are considered within the scope of this thesis: (1) a background on recent studies on micro-thermals, Kaimal and Businger (1970) and Gibson (1971); (2) a discussion of present concepts used to describe relevant

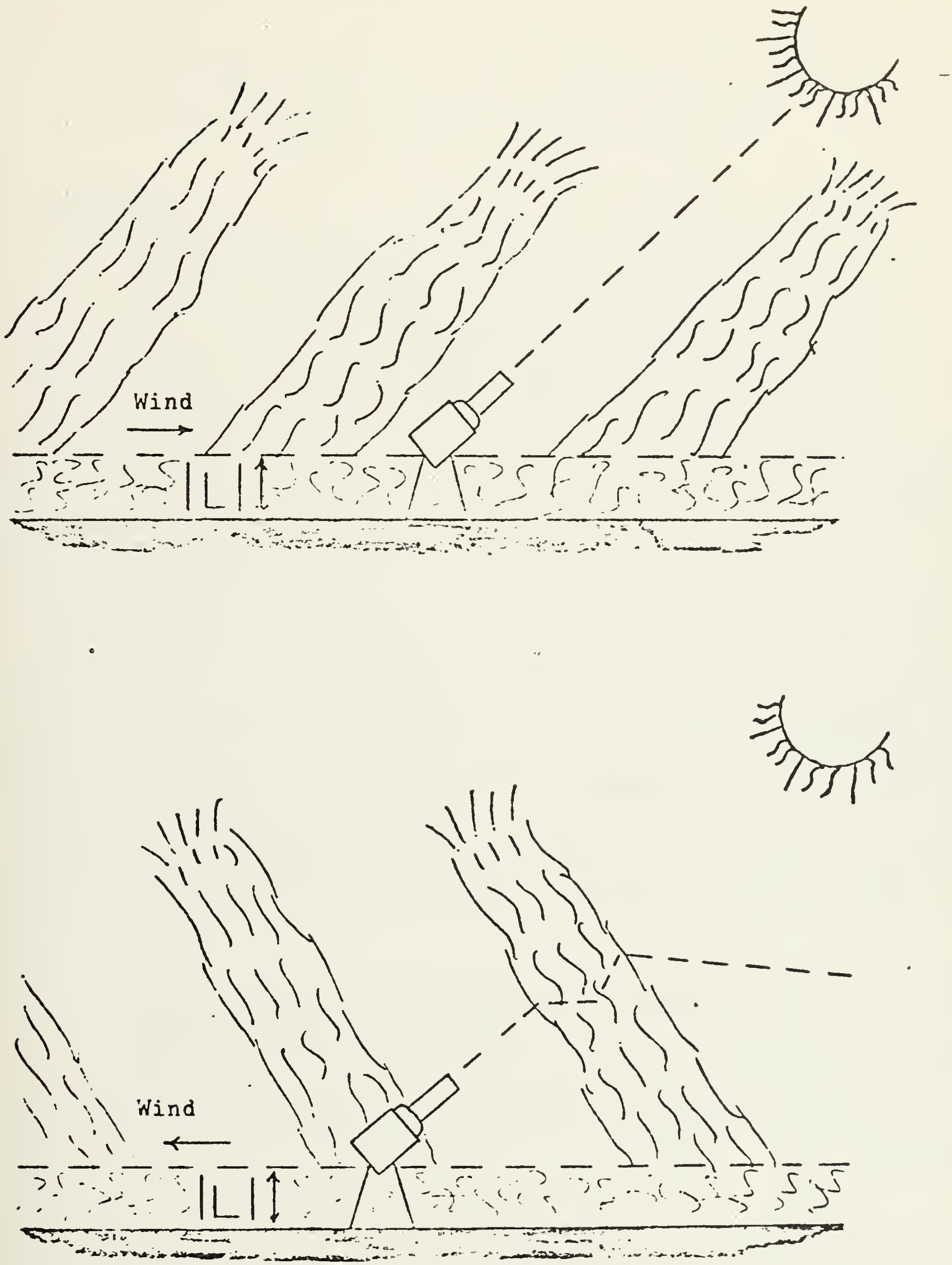


FIGURE 2. Thermal Convection Plumes Traveling in the Wind Past a Telescope, with Suggested Relationship of Seeing Quality to Sun-wind Orientation, Webb (1964).

properties of the surface layer; (3) the statistical procedures applied to the data and, finally; (4) a presentation of results and interpretations with respect to the applied problems of heat flux and optical wave propagation.

A. BACKGROUND

Micro-thermals are not a recent discovery. Their occurrence and features have been described in several investigations completed for a variety of objectives. They have also been assigned a variety of names (e.g., thermal plumes, saw-tooth ramps, and convective plumes). Most previous studies have dealt with occurrences over a flat land surface or in laboratories.

Two recent studies will be considered, one by Kaimal and Businger (1970) and the other by Gibson et.al. (1971). These studies represent two viewpoints on the formation mechanism. Kaimal and Businger treat the micro-thermals as being strictly a convective phenomenon, whereas Gibson et.al. suggests that their formation is due to vortices along the axis of the wind shear.

1. A Recent Study by Kaimal and Businger

Kaimal and Businger (1970) reported on results obtained in an investigation at the Air Force Cambridge Research Laboratories field site in southwestern Kansas. They examined data which revealed saw-tooth patterns in strip chart temperature traces (Figure 3). These data were observed from stationary sensors located at 5.6 meters and 22.6 meters.

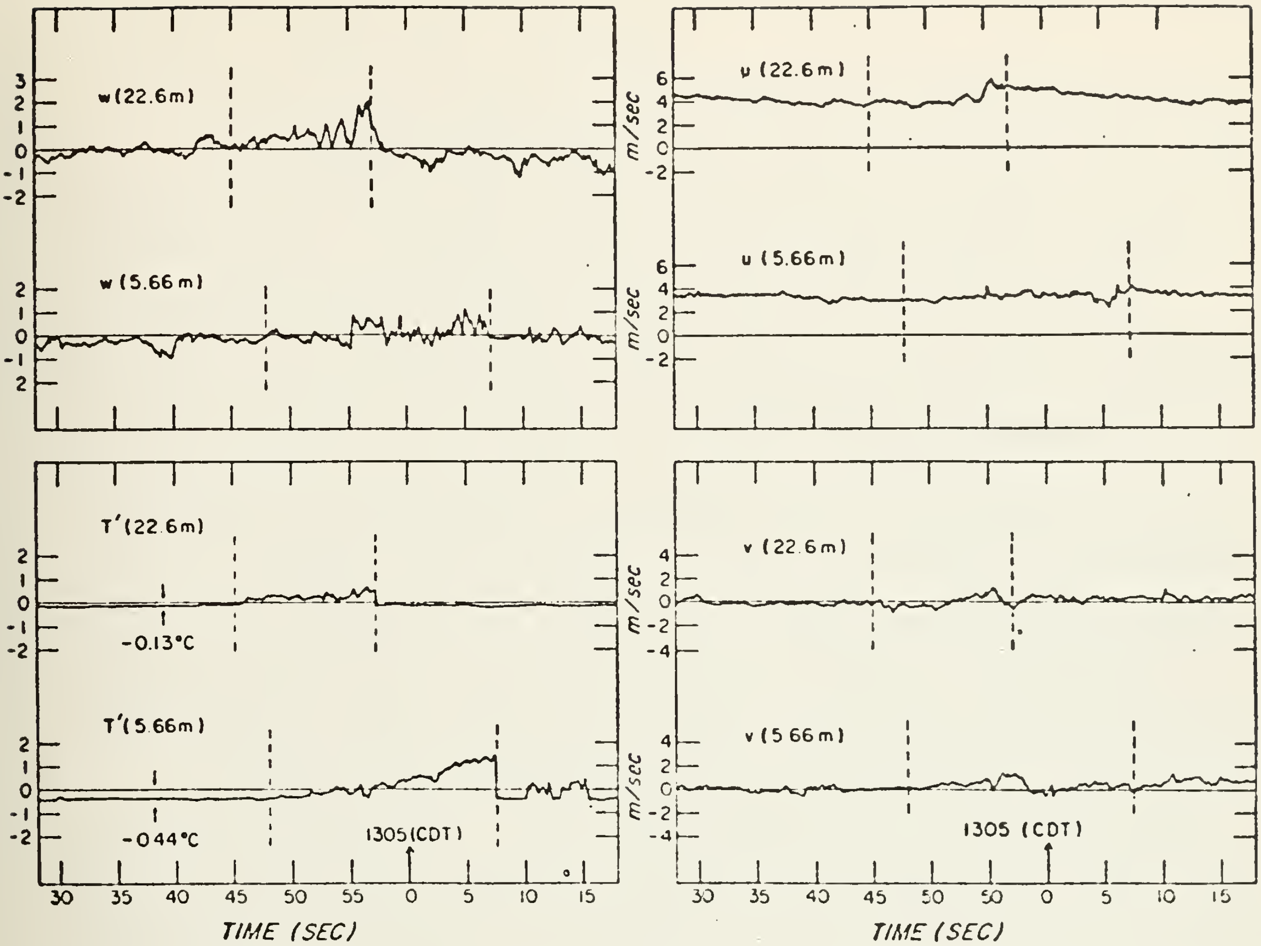


FIGURE 3. Traces of u, v, w, and T during Passage of the Convective Plume.

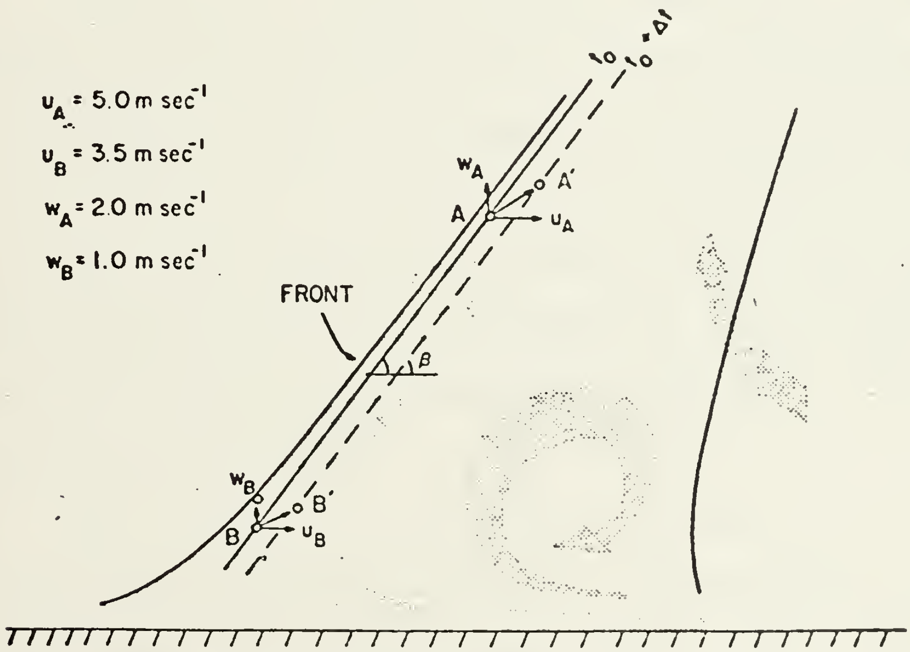


FIGURE 4. Two-dimensional Model of the Convective Plume, Kaimal and Businger (1970).

The analyses were based on the assumption that these features are due to convective phenomena.

The sensor mounting arrangement was well suited for examing the convective plumes' vertical extent and also their downwind tilt. Simultaneous velocity measurements allowed the examinations to be made of simultaneous features in velocity fluctuations and these appeared to be free of erratic fluctuations in the plumes. A large number of measurements permitted an investigation of the mean conditions associated with the plumes. For example, it was noted that the plumes were most evident in the forenoon periods when light winds and unstable lapse rates were the prevailing conditions.

Kaimal and Businger examined in detail what was defined as the "microfront". The front appears in the temperature trace as the sharp drop in temperature ending the ramp. Its presence was proposed to be due to stretching along the front with horizontal convergence perpendicular to it.

Analyses and interpretations supporting the proposed maintenance of the microfront also offer convincing evidence for the conclusion that the formation of the micro-thermals is due to convection. Because such a conclusion is in contrast to the interpretation by Gibson (to be discussed later) considerable detail will be presented on those features and/or computations which led to Kaimal and Businger's proposed "stretching mechanism".

With respect to the velocity fluctuations, it was noted that the vertical component of the velocity (w) increased from the lower level to the upper level. This is consistent

with the idea of stretching. Also the expected feature of w being predominately positive in the plume and negative outside the plume was more pronounced at the upper level. This suggests uniform subsidence in the ambient air with relative stretching, caused by buoyant acceleration, within the plume. Also, the horizontal component of the velocity (u) was found to increase behind the microfront which is consistent with the existence of convergence.

If stretching were occurring, as suggested by the kinematics of the velocity fluctuations, the tilt of the plume should also reflect an appropriate vector balance. To confirm that such a vector balance existed the tilt of the plume in the downwind direction was calculated using the following equation where subscript $_A$ denotes 22.6 meters and subscript $_B$ denotes 5.6 meters:

$$\beta = \tan^{-1} \frac{W_A - W_B}{U_A - U_B} \ .$$

From the velocity data in Figure 4 and the above equation, a tilt of 34 degrees was computed. Also, using the relation $U_T = U_A - W_A \cot\beta$ where U_T is the translation velocity, U_T was found to be 2.0 m/sec. In these data, the value of U_T occurred at a level below 0.5 meters, where Kaimal and Businger believed the plume began to assume its identity. A two-dimensional model of the convective plume was shown in Figure 4.

In comparing their results with theoretical models, Kaimal and Businger noted that:

> ". . . Although the literature on theoretical models for buoyant plumes is rather extensive (Priestley and Ball, 1955; Morton et.al., 1956; Turner, 1963; Telford, 1966; Barcilon, 1968), all of it deals primarily with idealized cases of free convection near the ground. These theories may be valid for axisymmetric plumes generated in the laboratory or those observed above 100m (Warner and Telford, 1967). But they are clearly not applicable to the type of plume discussed in this paper. Any theory developed for plumes near the earth's surface should incorporate (1) the sharp frontal boundary at the back of the plume, (2) the dissimilar shapes of the w and T traces within the plume, (3) the slope of the plume, (4) the entrainment mechanism, and (5) the momentum and energy balance within the plume."

On the basis of these observations and calculations, Kaimal and Businger concluded that the convective plume is basically a non-rotating system, transported at some near-surface mean velocity and that it derives its energy from buoyancy forces in the lowest layers. They also concluded that vertical stretching provides the means for maintaining the microfront and results in the constant tilt in the presence of a wind shear. It is noted that if this was not the case the plume would perhaps rotate around an axis parallel to the ground since the shear imbalance would be the only force acting.

Furthermore, it was observed that the magnitude of stretching implies that the pressure gradient inside the plume is greater than the hydrostatic pressure gradient. This result is relevant to existing surface layer analyses because the pressure work term is usually neglected in considerations of the turbulent kinetic energy balance, (e.g., Busch and Panofsky, 1968

Kaimal and Businger also computed the heat flux in the micro-thermals and found it to be the same for both levels. This was suggested to be due to the fact that the larger vertical velocity at the upper level compensates for the small temperature excess which occurred at this level relative to the lower level.

2. A Recent Study by Gibson et.al.

Gibson et.al. (1971) considered data obtained over the Pacific Ocean during February of 1969 and also data obtained in a heated laboratory jet. In the first case the underlying surface was warmer than the air and in the second case the reverse was true. In both cases, however, ramp-like structures were observed (Figure 5). In comparison to results considered by Kaimal and Businger, the heated jet results should not be related to buoyancy forces.

Analyses were performed to determine if the ramp-like structures in both cases had essentially the same statistical features and therefore could be due to the same process. It was noted, however, that the processes should not be dependent on buoyancy forces in the case of the jet because warm air was not rising, but rather was being forced downward.

It was suggested that in both cases the sharp thermal gradient develops on the sides of large eddies which are rotating with the mean vorticity of the shear flow, the vorticity in the shear flow being responsible for the transfer of hot fluids from the wake of the axis of the vortices.

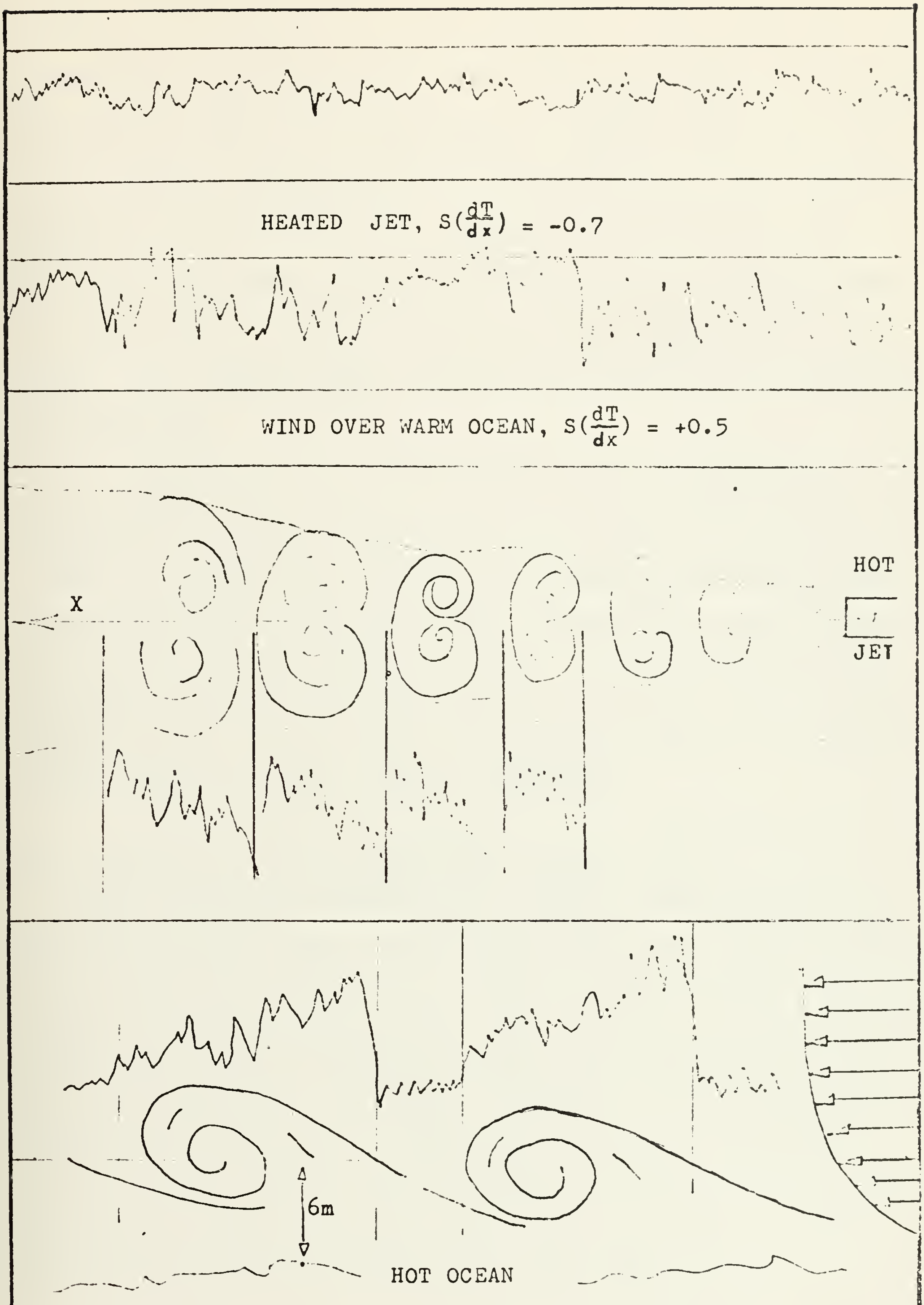


FIGURE 5. Results from Heated Jet and Hot Ocean, Gibson et al. (1971)

Statistics which measure the anisotropy of the turbulence were considered in the analyses. The anisotropy was examined by considering the value of the skewness of the downwind derivative of the temperature, $S(\frac{dT}{dx})$, which was found to be non-zero rather than zero as required in an isotropic regime. For the heated jet $S(\frac{dT}{dx})$ was -0.7 whereas it was +0.5 over the ocean. The significance of these results was that the absolute value in both cases was approximately the same. This implied that a similar mechanism was responsible in both cases.

Gibson et.al. also applied universal similarity hypotheses in their analyses. It was noted that in both cases the slopes of the spectra of dissipation fluctuations were about half the normal value. Furthermore, the results were nearly the same for both cases (the heated jet and the boundary layer) even though the Reynolds number for the two cases differed by two order of magnitude.

B. PROPERTIES OF THE STRATIFIED SURFACE LAYER

Mean properties defining the thermal stratification of the near-surface layer are very important in a study of this type. The micro-thermals have their origin in this stratified layer, grow upward through the layer and finally escape into the free atmosphere. The main features to be considered for this stratified layer is where free or forced convection processes are expected to be important and also if any possible wind-wave coupling phenomena may occur within it.

1. Convection Regimes

An important concept in analysis of the surface layer is the specification of forced or free convection. The free convection regime is of the most interest in this study. However, forced convection can be important especially in the region immediately adjacent to the waves. It is in the forced convection regime that the micro-thermals gain their identity, but as the micro-thermals ascend they pass into the region of free convection. The height at which the transition from forced to free convection occurs will decrease as the lapse rate increases and the wind speed decreases. This is because buoyancy forces begin to dominate the Reynolds stress forces.

Several criteria are used to delineate the existence of a free convection regime. The most widely used parameter is probably the Richardson number

$$R_i = \frac{g}{T} \cdot \frac{\partial \bar{T}}{\partial z} \Big/ \left(\frac{\partial \bar{U}}{\partial z}\right)^2 .$$

Several studies (Priestley, 1955, and Webb, 1965) have been directed solely toward determining a "critical Richardson" number (R_c). It is universally agreed that R_c is less than zero and that it varies somewhat with the given conditions and height. A good approximation is that at a height of 1.5 meters the critical Richardson number lies between the limits of -0.018 and -0.10.

Webb (1964) suggested that the break between free and forced convection becomes evident at a value of $|Z/L|$ as low as 0.03. Based on Z/L and the lapse rate, Webb viewed

the surface layer as consisting of three regions and fortuitously related each region to the appearance of the temperature traces as shown in Figure 6. It is noted that in Figure 6 T and W exhibit random fluctuations yet maintain a positive correlation. This region corresponds to an area where $|Z/L| < 0.03$, a region of forced convection.

In the middle region, $.03 < |Z/L| < 1$ (the free convection regime), there are noticeable fluctuations that are distinct positive pulses, appearing as ramps which occur simultaneously in both the T and W traces. These pulses become more pronounced with height, clearly representing buoyant thermals. In the upper region $1 < |Z/L| < 10$ (still free convection) the thermals are still more noticeable and are accompanied by periods of no fluctuations. The latter represent periods in which cooler air was descending from higher levels.

Priestley (1968) arrived at similar conclusions in a discussion of the onset of free convection. He described disturbances in the temperature traces which were similar to the micro-thermals. These disturbances were associated with ascending air and were separated by well-defined and nearly fluctuation-free periods in the descending air. Priestley suggested that even under conditions exhibiting free-convection aloft, forced convection will dominate close to the surface if any wind is present.

2. Wind-Wave Coupling

An important consideration in an investigation with data of this kind is the possible influence waves could have

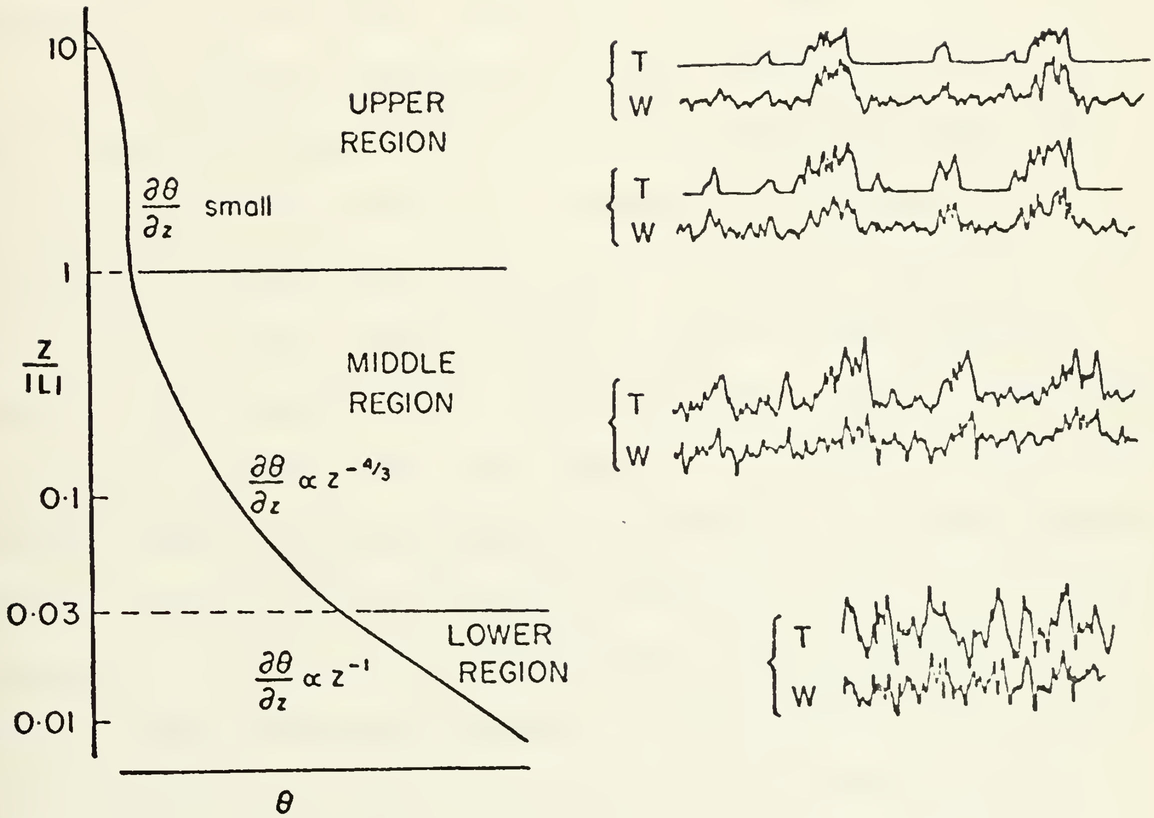


FIGURE 6. Lapse Condition: Form of the Potential Temperature Profile and Nature of Fluctuations of Temperature and Vertical Velocity Component. A Recording Time of 5 min. is Represented in the Upper Traces, Webb(1964).

on the turbulent airflow. The distinctive feature of the layer adjacent to the waves is the presence of the waves themselves through which there is direct transfer of energy and momentum. Although hypotheses on the mechanisms responsible for the transfer of energy from the wind to the waves have existed for some time, it has only been in the last few years that significant progress has been made in theoretical formulations of wind-wave coupling (Miles 1957, Yefimov 1970).

The dynamics inherent in these formulations are that wave-induced motions interact with the turbulent shear flow at levels above the surface to enhance the transfer of momentum and energy toward the wave. One such level of interaction is the 'critical level' which is the height at which the wind speed equals the wave speed. If the wave speed is much greater than the wind speed in the surface layer, the critical level is effectively at 'infinity'. In this respect, Yefimov (1970) obtained numerical solutions from a non-linear formulation of the previous wind-wave coupling models which revealed that turbulent transfer is influenced by the interaction between the wave-induced motion and the shear flow irrespective of the existence of a 'critical level'.

Laboratory and natural regime data indicate that some verifications of the theoretical formulations do occur. Most apparent in observational results is the existence of measureable wave-induced motion in the airflow. However, because most observations are made from fixed levels above the near water level, these results could reflect a simple

streamline distortion by the wave, Figure 7a. A few investigations, however, have yielded results which indicate that the wave-related fluctuations are responsible for significant contributions to the momentum transfer. Such a result is important because it supports those processes predicted by the theoretical formulation.

Observational investigations which have provided evidence of wind-wave coupling are, from laboratories, Stewart (1970), Lai and Shemdin (1971), Karaki and Hsu (1968): from the natural regime, Elder et.al. (1970), Yefimov and Sizov (1969) and Davidson and Frank (1972). The latter investigation was completed on data considered in the present study and relevant results will be presented along with the description of general conditions.

An important implication of wind-wave coupling is that the turbulence in the airflow is more 'organized' than that over a rigid surface. This possibility was emphasized by Stewart (1967) in a consideration of the validity of existing formulae for estimating boundary fluxes over the sea. Stewart noted that the wind-wave coupling theories predicted unattenuated kinetic energy transfer, from a level above the surface to the surface. Therefore, the total kinetic energy balance for this transfer would be:

$$\frac{\partial}{\partial z}\left[\overline{uw}\ \overline{U} + \overline{w\left(\frac{p'}{p} + \frac{u^2 + v^2 + w^2}{2}\right)} \right] = 0$$

or

$$\overline{uw}\ \overline{U} + \overline{w\left(\frac{p'}{p} + \frac{u^2 + v^2 + w^2}{2}\right)} = \text{constant}$$

Because uw is a constant while u goes to zero as the surface is approached in shear flow, the remaining term would have to increase to keep the sum a constant. Stewart suggested that such a compensation implied the existance of motion which is more organized than that associated with a fully turbulent flow over a rigid boundary. Specifically, Stewart questioned the validity of existing transfer coefficients for estimating sensible heat and momentum fluxes near a wave surface.

The existence of organized motion in this region would enhance the formation and maintenance of micro-thermals based on the assumption that a fully turbulent regime would not allow the large thermal gradient associated with micro-thermal formation to exist.

Kitaygorodskii (1969) also considered the problem of assigning emperically derived transfer coefficients to an air layer wherein the waves may have a significant influence. He expressed the fact that the largest contribution to ΔU, $\Delta \theta$, and ΔE arises in the near surface layer. He suggested, therefore, that the transfer coefficient C_u, C_θ, and C_E should depend heavily on turbulent processes near the waves. Kitaygorodskii examined results from several over-water observations and concluded that a significant portion of the fluctuations above a sea surface were intimately related to wind-wave coupling. In particular, he examined the influence that wind-wave coupling may have on the mean wind profile.

Wave-induced distortions to the mean wind profile are of interest in the present study because of the suggestion

by Gibson et.al. (1971) that the micro-thermals are associated with the vortices in the shear. In a two-dimensional analyses the mean vorticity in the flow is determined by $\partial\bar{U}/\partial z$. The occurrence and intensity of the vortices would, therefore, be related to the stability and magnitude of the mean shear. Interestingly, (in a laboratory experiment), Stewart (1970) observed that the mean shear differed between the regions over the trough and crests of the wave, Figure 7b. One would have to conclude that the adjustment of the mean shear to different phases of the surface wave would involve parallel adjustments or changes in the mean vorticity. Such changes would, of course, involve instabilities associated with the formation of vortices inherent in Gibson et.al.'s (1971) proposed mechanism for micro-thermal formation.

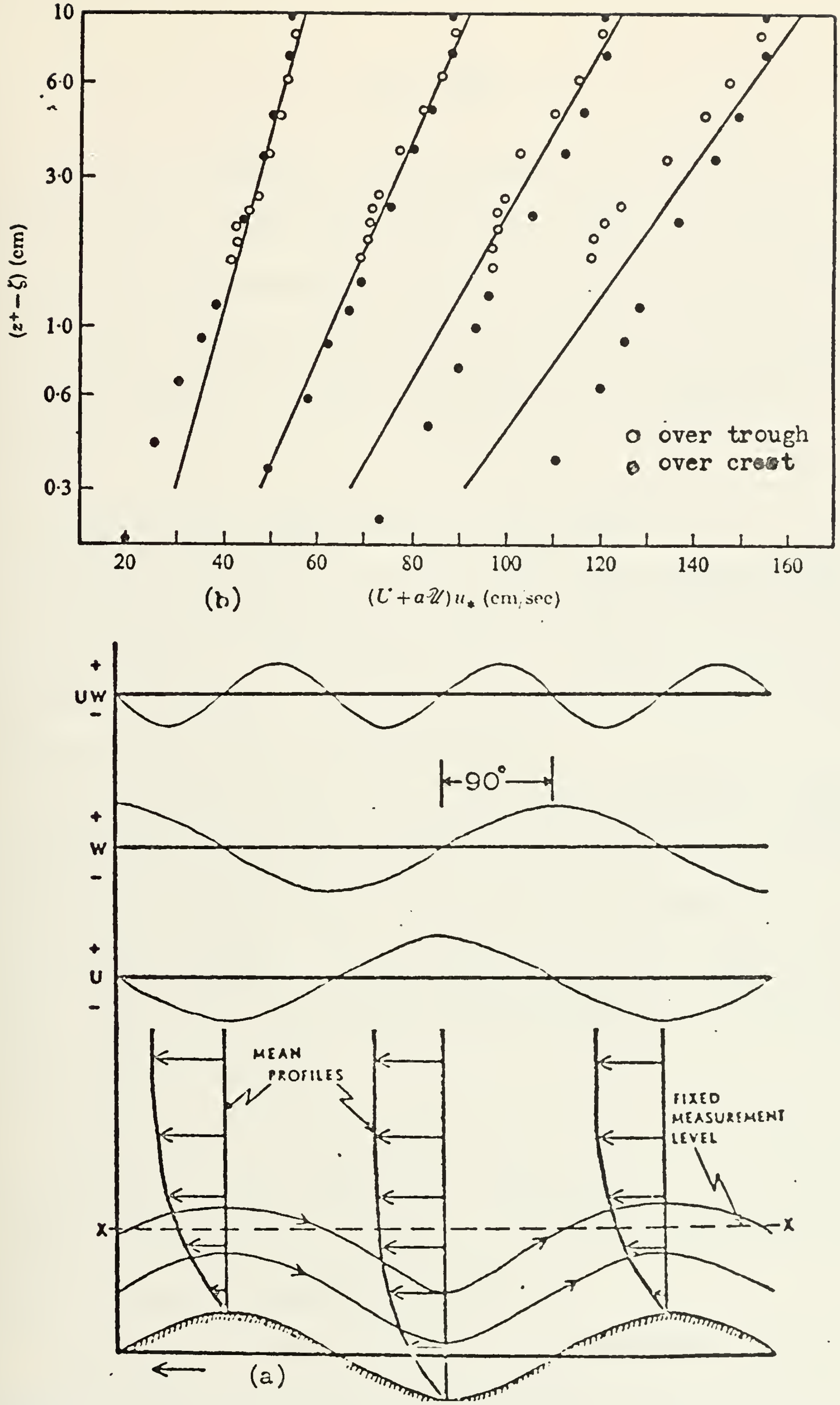


FIGURE 7. (a) Potential Flow Prediction for Velocity Fluctuations from a Fixed Sensor over Progressive Waves, (b) Mean-wind Velocity as a Function of Wave Phase vs Instantaneous Height above Water Surface, Stewart (1971)

II. DATA

The data analyzed in this study were obtained in 1968 by University of Michigan personnel under a contract with the Office of Naval Research. Details of the acquisition and processing of these data were described by Davidson (1970). Relevant aspects of that description are summarized in this section.

A. LOCATION AND DESCRIPTION OF THE TOWER

The data examined in this study were from two days (26 September and 27 September 1968) of observations on Lake Michigan. Figures 8a and 8b depict the location and general construction of the research tower.

As mentioned previously, the data represents simultaneous measurements of wind (u and w), temperature fluctuations and waves from a fixed tower. Velocity and temperature measurements were obtained at two different levels above the mean water level, and the waves were measured at a point directly below the air sensors.

The features of the sensor mounting arrangement are shown in Figure 9a. The plumb line arrangement of the sensors enabled examination of phase relations between the waves and the turbulent components in the air.

A constant temperature hot wire anemometer using two wires in an X-configuration was used to measure the turbulent

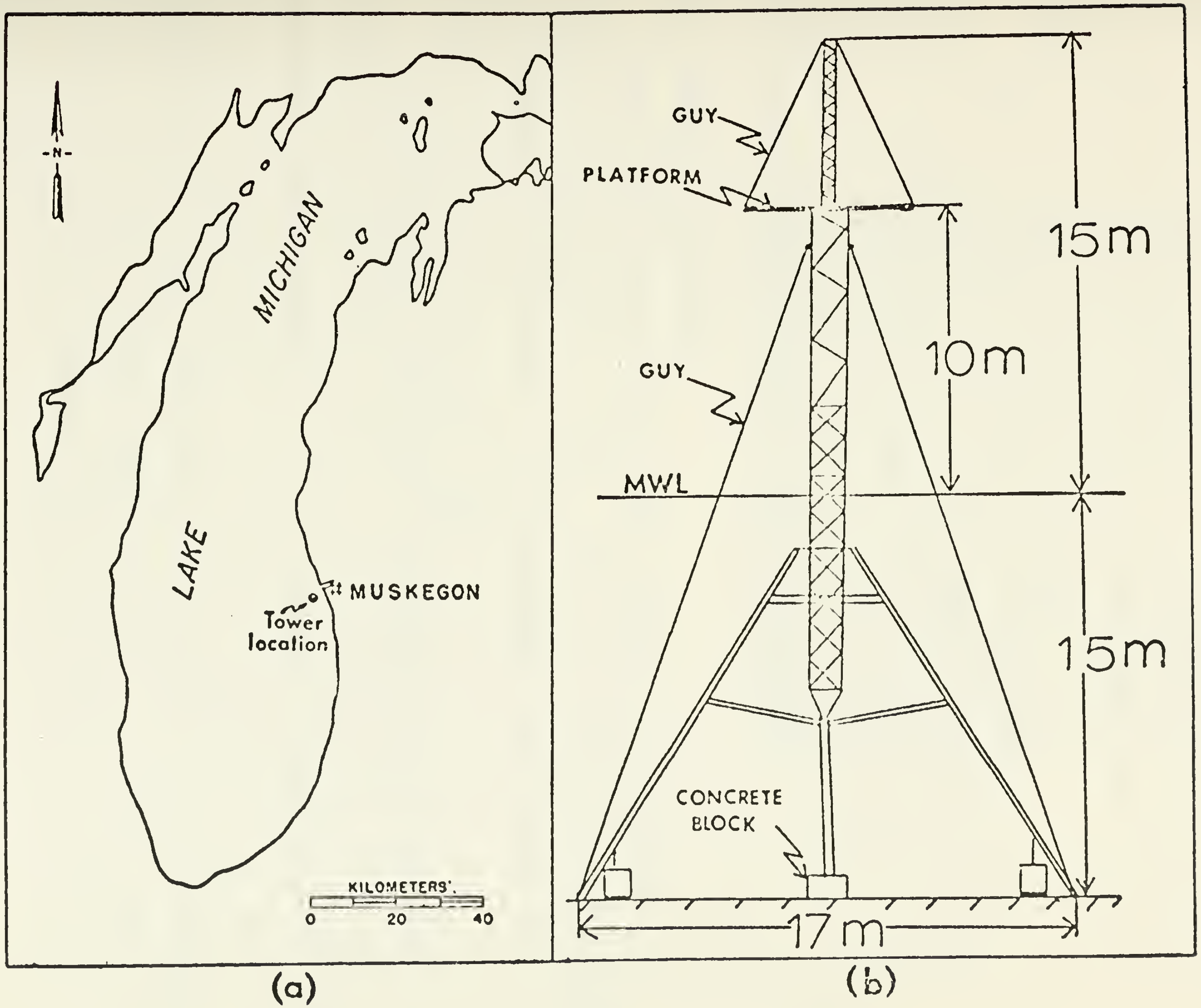


FIGURE 8. (a) Location and (b) Structure of Tower.

velocity components (u and w). The temperature fluctuations were measured using a resistance thermometer, incorporated in a Wheatstone bridge. For a one degree (Celsius) temperature change an output signal of 125 millivolts was used. Laboratory testing indicated a resolution of temperature measurement to an accuracy of 0.05° C. A capacitance gauge and bridge system were used to measure the waves.

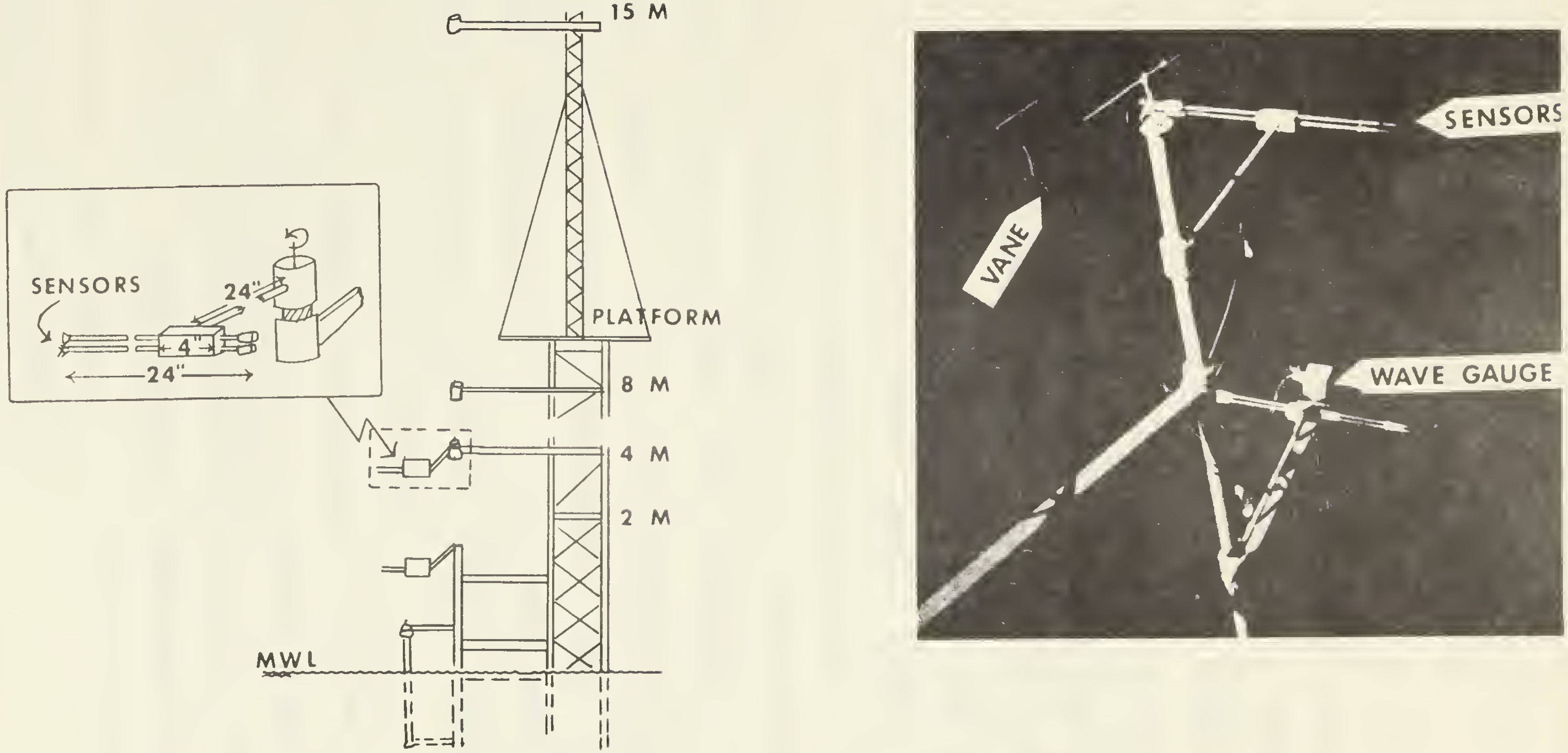
Figure 9b shows the sensors as they appeared on the vertical pipe during one of the periods considered in this study. The wind vane was used at all levels to monitor the direction of the mean wind with respect to the sensors. The wave gauge appears directly below the sensors.

B. GENERAL CONDITIONS

The three periods which were examined are the same as delineated by Davidson (1970). They are Period 5[1] (1100-1120) and Period 7[1] (1355-1415) on 26 September and Period 9[1] (1140-1200) on 27 September 1968.

Considering the stability with respect to the air-sea temperature difference, $T_a - T_s$, the largest value (-5.4 C) occurred during Period 7 and the smallest difference (-3.3 C) occurred during Period 9. In Period 5, $T_a - T_s$ was -5.0°C. Figures 10-12 depict the vertical structure of the temperature during the three periods. The lapse rate is of the order of -.25 C per meter as compared with the neutral atmosphere

[1] The period numbers correspond to those used in the first report on these data, Davidson (1970).



(a)

(b)

FIGURE 9: Sensor mounting arrangement on tower; (a) components and vertical array, "plumbline", (b) picture of sensors during measurement period.

value of -.01 C per meter. Therefore, the instability of all three periods is evident. The mean wind speed as shown in Figure 13 (a) and (b) decreased from 6 m/sec in Period 5 to 5 m/sec in Period 7 and to 3.5 m/sec in Period 9.

Considering stability on the basis of both air-water temperature difference and wind speeds, the Richardson number decreased from -0.56 during Periods 5 and 7 to a minimum of -0.71 during Period 9. Because the Richardson number was determined for the entire 20 minute period, it may not necessarily represent the actual conditions during the occurrence of a micro-thermal. This is especially true in Period 9 when conditions were unsteady. Also, the values are representative only at the 1.5 meter level. However, because the values of the Richardson number are less than the order of the critical Richardson number, all of the periods should exhibit features associated with free convection.

Additional parameters must be considered in this study because the data were obtained over waves. Since the micro-thermal gains its identity in the lower level and rises, it is convenient to define the "critical level". During Periods 7 and 9 this level was above 15 meters.

However, during Period 5 the critical level was closer to the surface because of the stronger winds. Another parameter that may have had an influence on the micro-thermals was the wave height. During Period 5 the significant wave height was 48 cm. This decreased to 38 cm in Period 7 and then increased to 46 cm in Period 9.

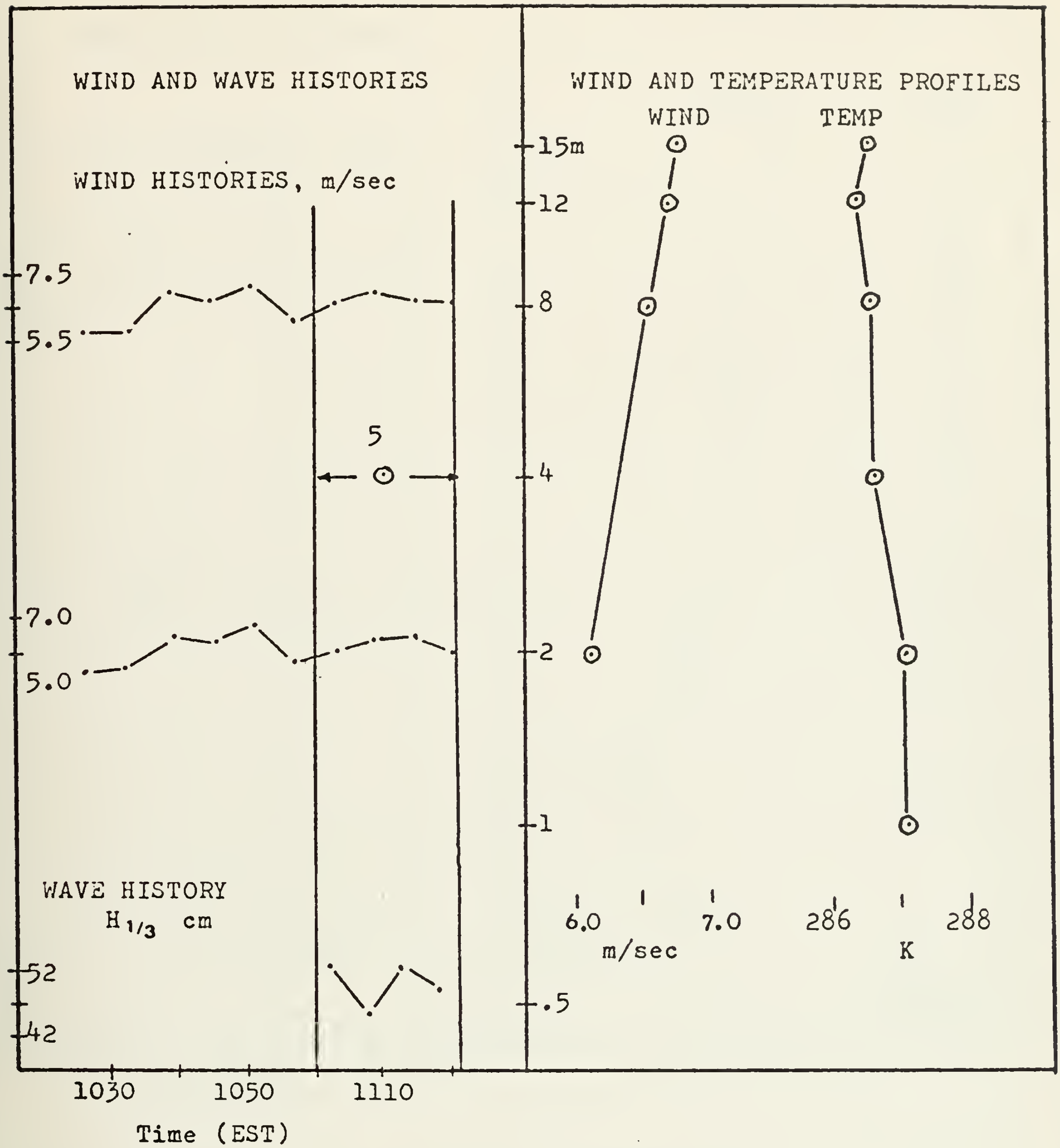


FIGURE 10. General Wind, Wave, and Temperature Profiles for Period 5.

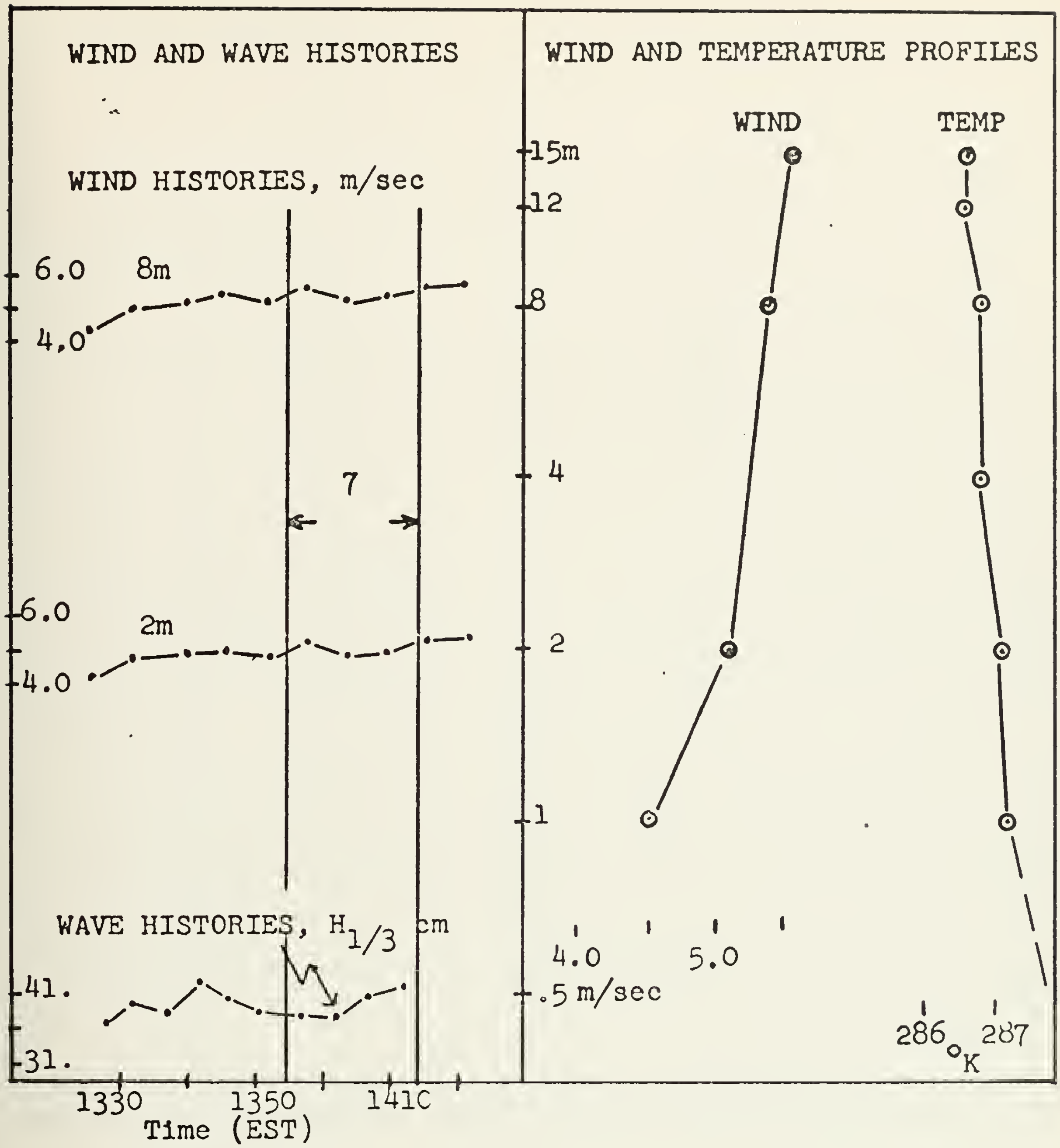


FIGURE 11. General Wind, Wave, and Temperature Profiles for Period 7.

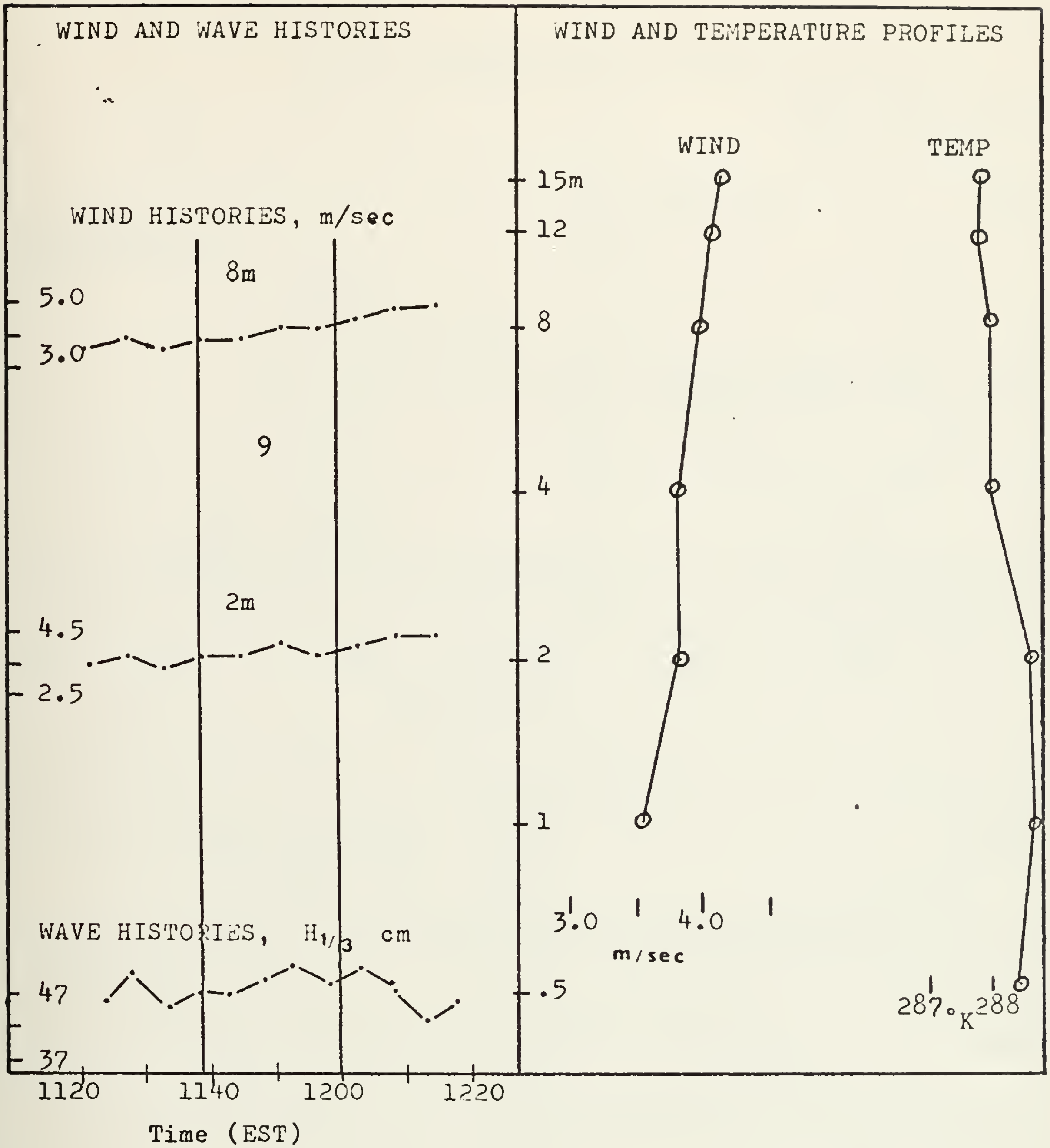


FIGURE 12. General Wind, Wave, and Temperature Profiles for Period 9.

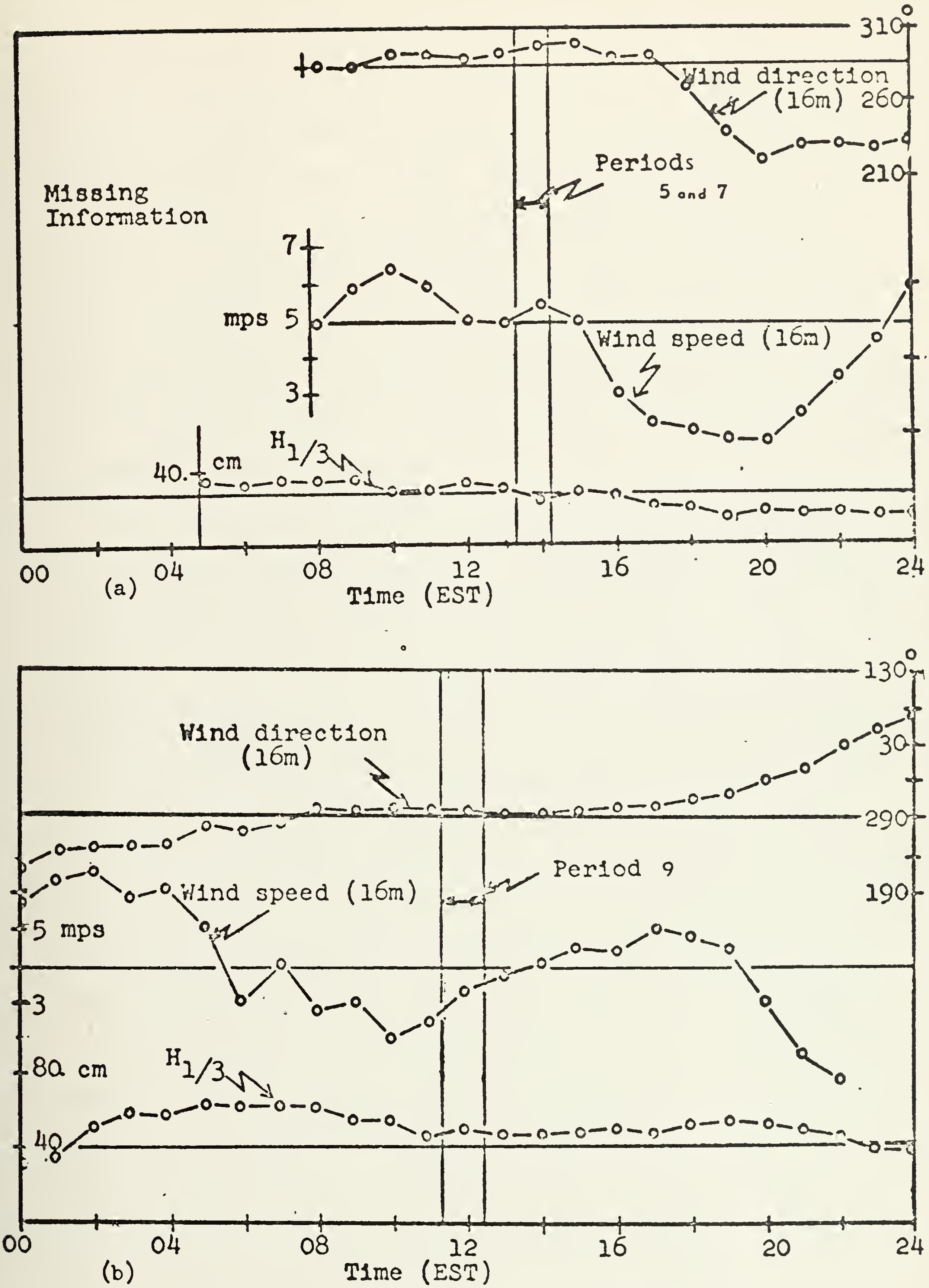


FIGURE 13. General Wind Conditions: (a) Periods 5 and 7, 26 September, (b) Period 9, 27 September.

Velocity variance, covariance spectra and wave variance spectra for the three periods appear in Figures 14, 15, and 16. The presence of wave-related fluctuations in the airflow is evident in the coincident peaks in the velocity and in the wave variance spectra. These peaks appear for all periods and for both u' and w'. Evidence of features predicted by wind-wave coupling also appear in the cospectra. Extrema occur in the cospectra at frequencies corresponding to the wave spectra peaks. These extrema represent both enhanced and decreased momentum transfer when compared to that occurring at neighboring frequencies.

Wind and wave conditions associated with the periods on 26 September, Figure 14 and 15, suggest that the "critical level" was in the vicinity of the measurement levels. The existence of enhanced downward momentum transfer for the periods is observed in the data. On 27 September, however, the wave speed corresponding to the spectrum peak was much greater than the mean wind speed in the surface layer. Therefore, the latter period should not reflect the feature associated with the dynamics of the 'critical level'. The oscillatory appearance for the wave-induced stress is in fact a predicted feature for such a wind-wave condition.

It is evident from these figures and the preceding discussion that processes related to wind-wave coupling were occurring during all of these periods. The present level of understanding of these processes does not allow them to be applied in an interpretation of the differences between the

periods with respect to micro-thermal occurrences. It should be noted, however, that during all of these periods a significant portion of the fluctuations in the velocity field and a significant portion of the momentum transfer were associated with wind-wave coupling.

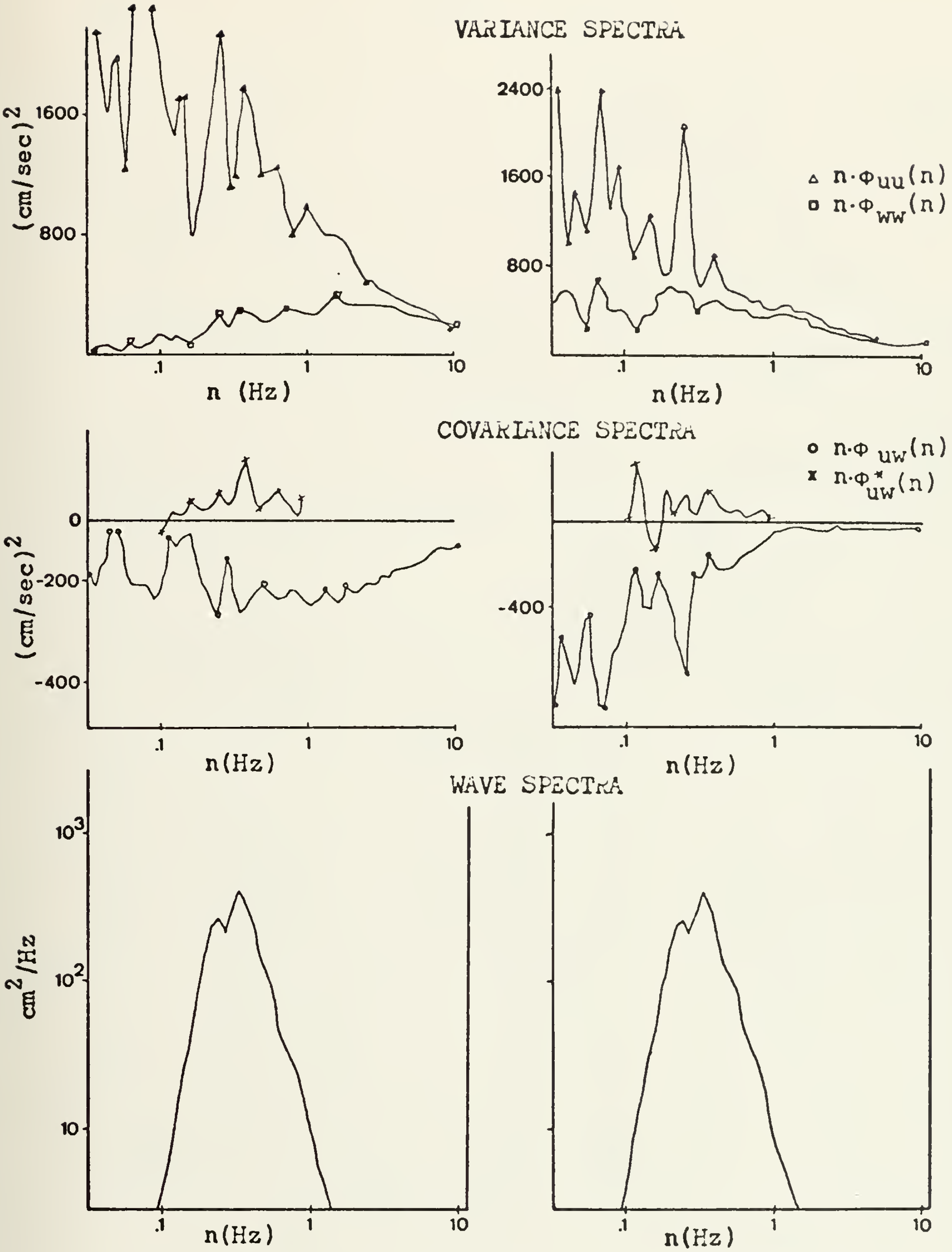


FIGURE 14. Velocity Variance and Covariance Results and Wave Spectra for 26 September, Period 5, with 1.5 meter level on the Left and 4.0 meter level on the Right.

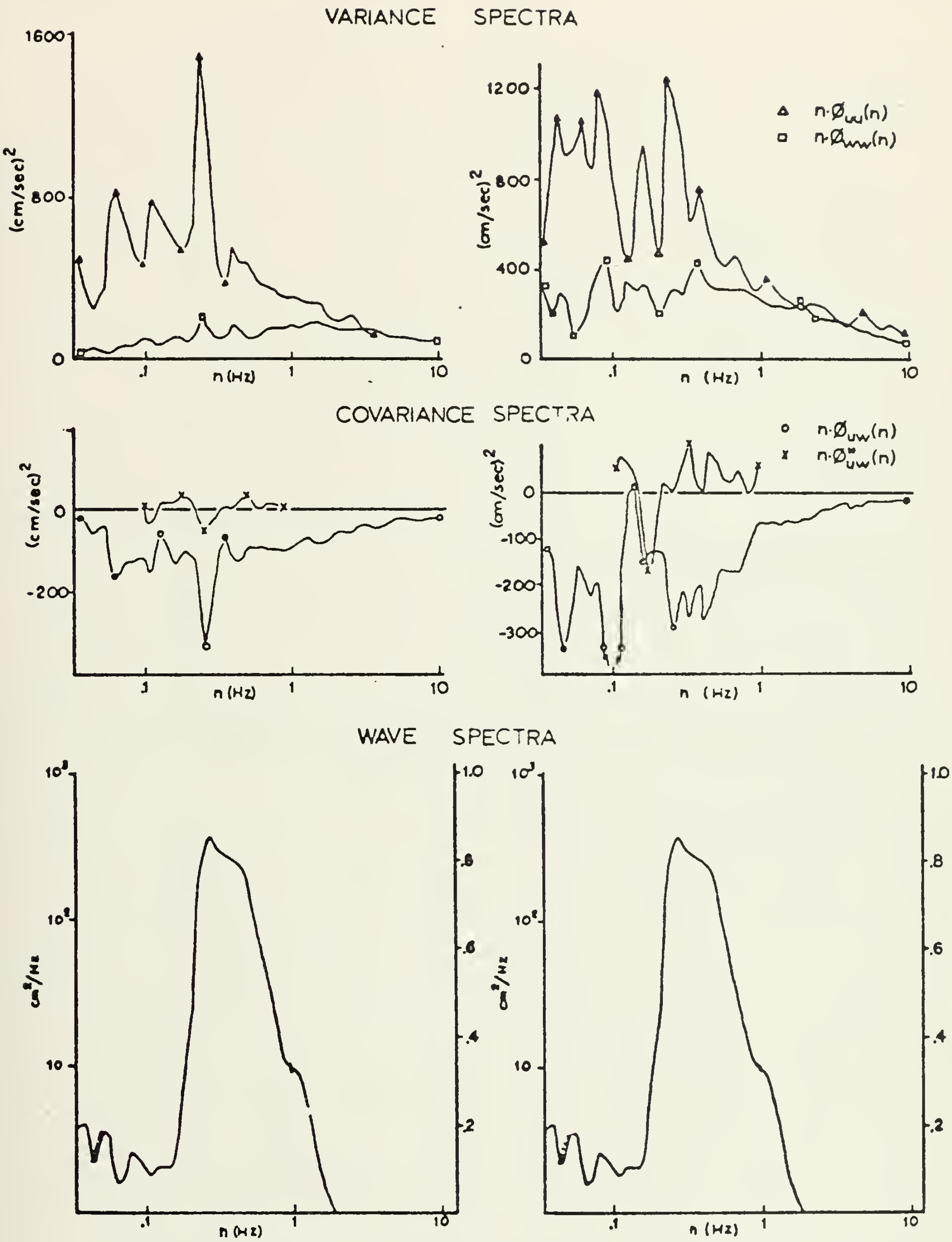


FIGURE 15. Velocity Variance and Covariance Results and Wave Spectra for 26 September, Period 7, with 1.5 meter level on the Left and 4.0 meter level on the Right.

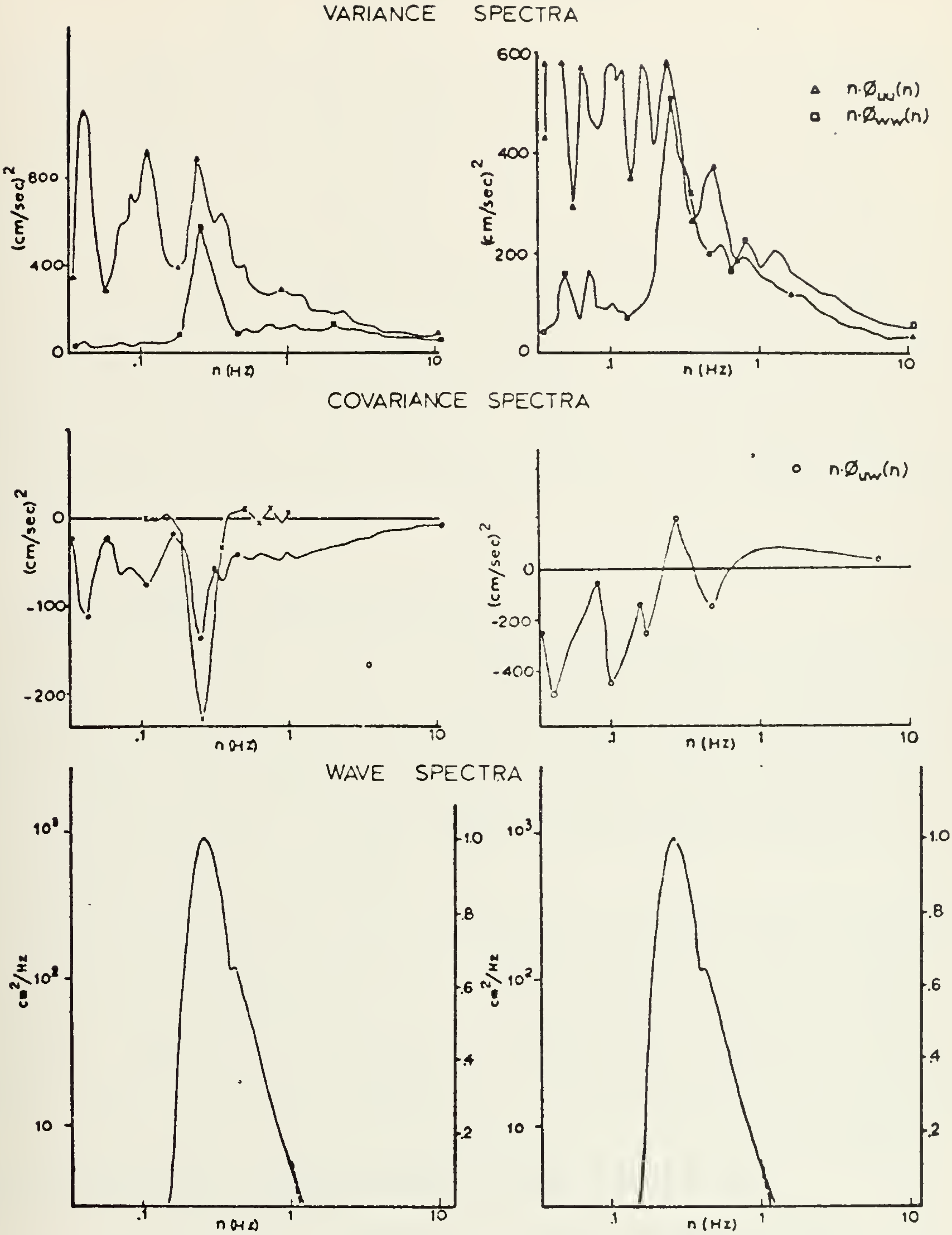


FIGURE 16. Velocity Variance and Covariance Results and Wave Spectra for 27 September, Period 9, with 1.0 meter level on the Left and 2.0 meter level on the Right.

III. STATISTICAL PROCEDURES

The initial statistical procedures applied in this study were those which provided information as to whether the micro-thermals existed in this data. Once their existence was established, the exact location of the start of the ramp and the trailing edge of the microfront was determined. This information was stored, along with the data within the micro-thermal, for further computations regarding the heat flux ratios and the relations between the velocity, temperature, and waves.

A. MICRO-THERMAL IDENTIFICATION

In order to make the necessary calculations on the micro-thermals, it was necessary to objectively identify them in the records. An objective scheme was necessary due to the fact that there was a large amount of data and numerous computations were required.

Statistical procedures for classifying the micro-thermals required the specification of a standard (or normal) micro-thermal. Figure 17 graphically depicts the characteristics which were considered briefly in the introduction; these are

1. a gradual rise of temperature followed by a sharp drop producing an asymmetrical saw-tooth pattern;

2. simultaneous occurrence of the pattern in the temperature traces from two measurement levels arranged in a plumb line;

3. an average three second duration for each pattern;

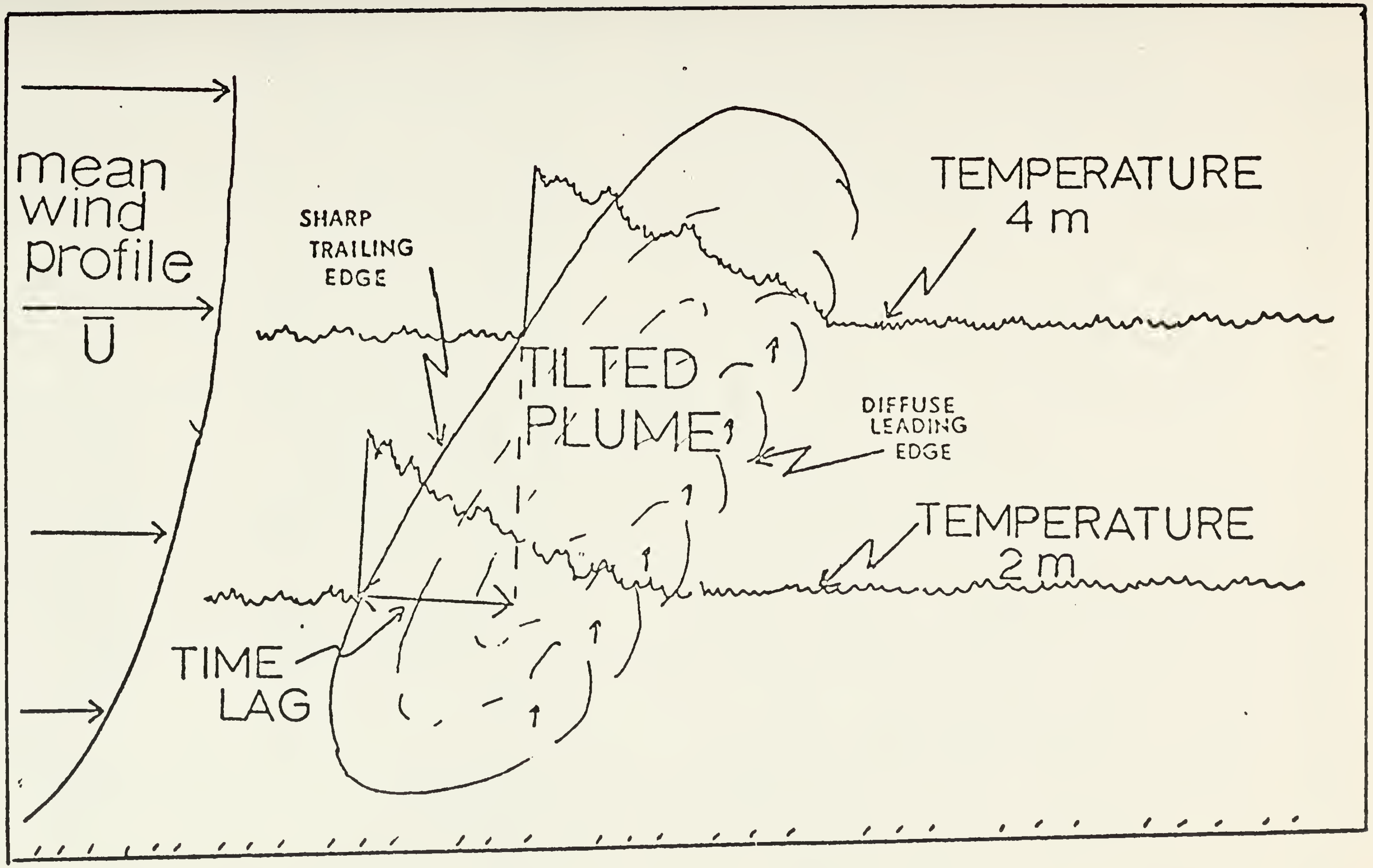


FIGURE 17. Schematic of Thermal Plume in Shear Flow, Gill (1971)

4. separation of patterns by quiescent periods; and

5. fluctuations contributing to the patterns which are always positive with respect to the mean value of the recorded traces.

As a first step, continuous traces of the 20 minute data sets were prepared to determine if micro-thermals were present, (see Figure 18[2] as an example). Once those periods which had micro-thermals were identified, the objective scheme was used to isolate and store them for further computations.

Since the fluctuations associated with the micro-thermals were always positive with respect to the mean value, the skewness was used in the identification procedures. The skewness is defined by the following equation for a variable X where $X' = X-\bar{X}$ and X and $\bar{X}$ are instantaneous and mean values respectively:

$$S = \frac{\overline{X'^3}}{(\overline{X'^2})^{3/2}}$$

Since skewness incorporates the sign of the fluctuation, it is an ideal statistic for identifying the micro-thermals. Recall that Gibson et.al. (1971) used skewness in their analyses of temperature and velocity fluctuations. In this study however, skewness was applied to temperature as well as $\frac{dT}{dt}$ the latter being Gibson's only consideration.

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[2]The strip chart record appearing in Figure 18 for Period 5 depicts the waves, , in the lower trace, the ratio of the skewness in the second trace for 1.5 meters and vertical velocity W for 1.5 meters in trace three and temperature T for 1.5 meters in trace four. Traces five, six and seven are the skewness ratio, vertical velocity and temperature respectively for 4.0 meters.

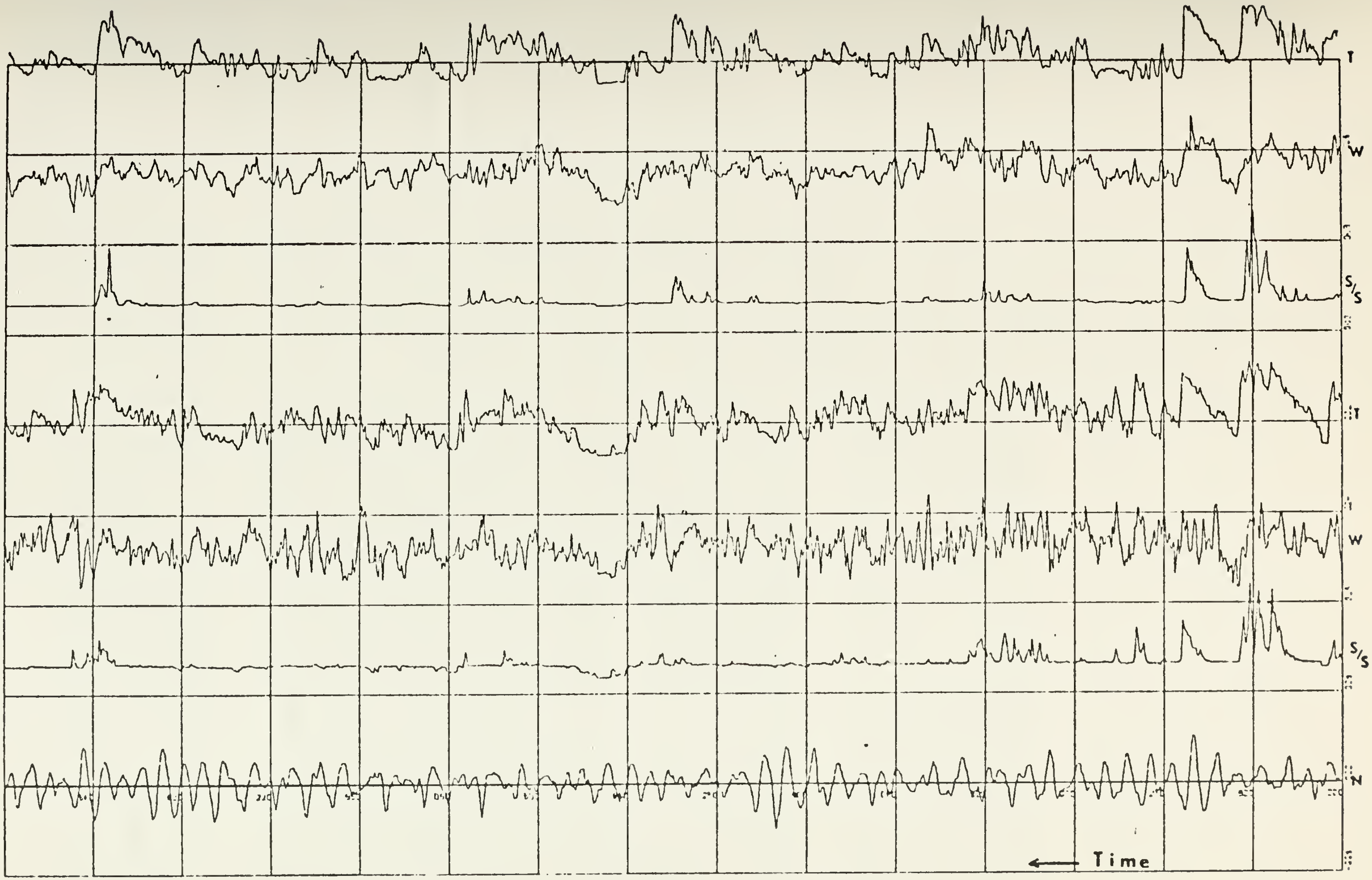

FIGURE 18. Sample Strip Chart Traces depicting Evidence of Micro-thermals.

The skewness was computed for both levels in each 20 minute period. Next, T'^3 at each point within each period was computed and the ratio of T'^3 to the average skewness S for the period containing that point was computed. The positive fluctuations in this ratio are readily related to positive fluctuations in the temperature traces as shown by traces two and five in Figure 19.

In order to define the beginning of the micro-thermal, different values of this skewness ratio were examined and a final value of 3.5 was selected. In order for a micro-thermal to be defined, an average value of 3.5 had to be maintained over at least five points.

After a micro-thermal was identified it was necessary to determine the trailing edge or the microfront. This was relatively simple due to the large temperature drop at this point and was determined by comparing the average skewness of the temperature value over each sequential set of three points with the value at the start of the micro-thermal. This was refined by including a comparison of the value of the temperature at each point with that at the preceding point in the micro-thermal. The combined procedures gave the exact location for the trailing edge of the micro-thermal which is needed, for example, in computations of heat flux in the micro-thermals.

A final criteria imposed in plume identification was the need for the simultaneous occurrence of the above patterns in the temperature trace and in the skewness ratio for both levels.

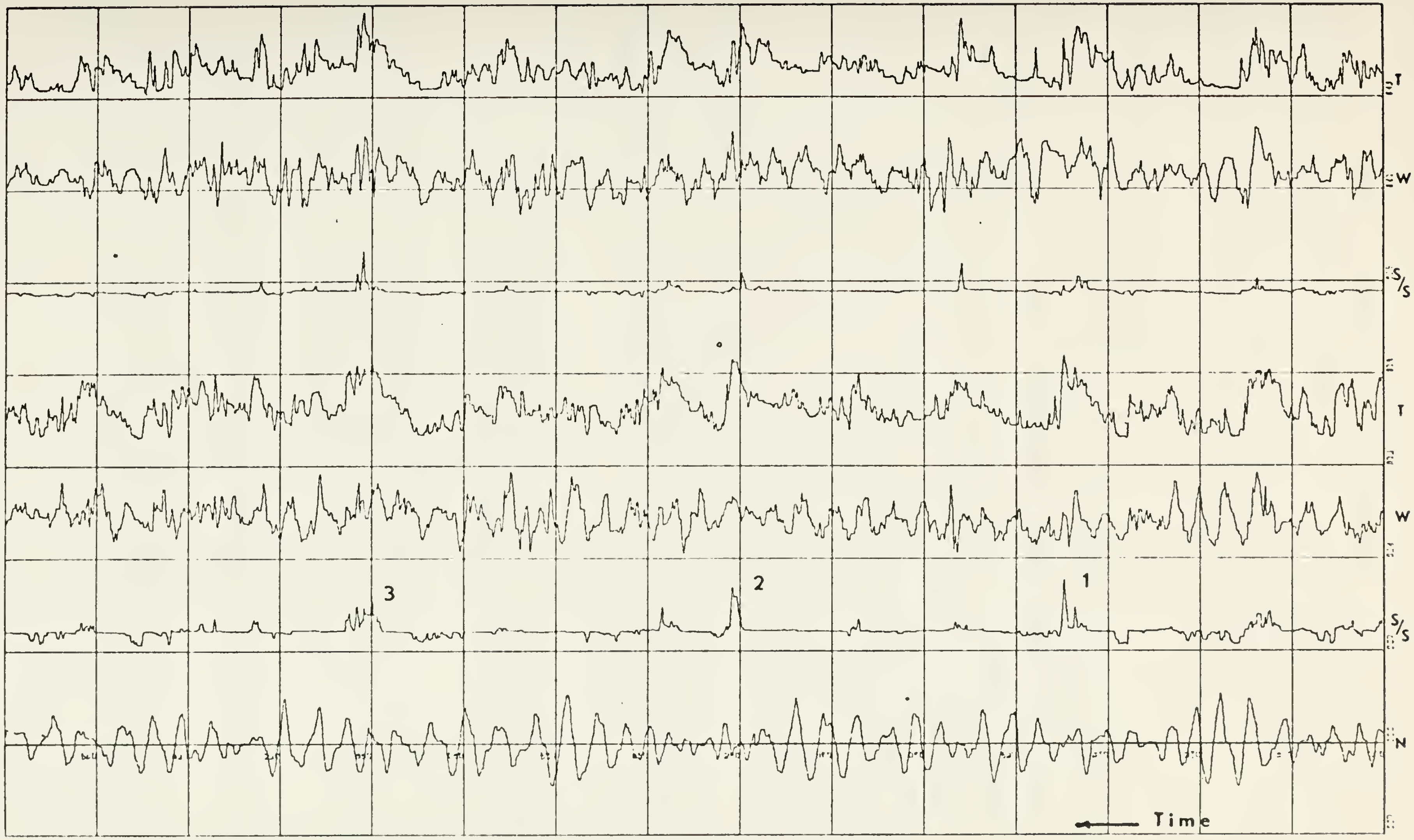

FIGURE 19. Sample of Correlation of Positive Fluctuations in Skewness Ratio and Positive Temperature Fluctuations.

Once a micro-thermal had been identified by the preceding tests, associated parameters (wave height, velocity, and temperature values) were stored for additional computations involving the heat flux and for comparison of velocity and temperature fluctuations within these intervals.

B. HEAT FLUX COMPUTATIONS

The first step in computing the turbulent heat flux in each period was to remove the means from the temperature and vertical velocity record to yield w' and T'. The product of the vertical velocity w' and temperature T' were then summed over a 20 minute period for each level in order to determine the total heat flux during each period at each level. Next, the heat flux within the previously defined micro-thermals in each period was computed.

The heat flux associated with micro-thermals was subtracted from the total heat flux and the following ratio calculated:

$$R = \frac{\overline{w'T'}\text{ (plume)}}{\overline{w'T'}\text{ (total)}-\overline{w'T'}\text{(plume)}} \cdot \frac{\text{(\% trace without plumes)}}{\text{(\% trace with plumes)}}$$

This represents the average relative magnitude of the flux inside the micro-thermal to that which is solely a function of the shear induced turbulence.

C. RELATIONSHIPS BETWEEN FLUCTUATIONS IN VELOCITY (u and w) AND TEMPERATURE

The relationships between temperature fluctuations and the w component of the velocity fluctuations were examined

using the skewness of the w component. The upward motion associated with the micro-thermals should result in positive values of the skewness in any interval previously determined to represent a micro-thermal.

IV. RESULTS AND INTERPRETATIONS WITH RESPECT TO APPLIED PROBLEMS

The results and interpretations presented in this study are grouped in three discussion areas. First, the characteristic features of observed micro-thermals are described. Second, the possibility of the wave's influence on the structure and occurrence of micro-thermals is examined. Third, the effect micro-thermals have on heat flux estimates and optical wave propagation are discussed.

A. DESCRIPTION AND CHARACTERISTIC STRUCTURE OF MICRO-THERMALS

A description of observed micro-thermals includes the large temperature drop at the upwind edge, referred to as the microfront. Previous discussions in this study described details of previously reported results. The completeness of the measurements providing these data allow the microfront to be examined with respect to simultaneous features occurring in other variables.

Several of the ramp-like structures appear in Figure 20. Three of these are indicated by the letters A, B and C. In all cases the large temperature drop at the upwind edge is quite evident.

In general the temperature traces exhibit a fairly well-defined temperature base wherein fluctuations are random and continuous about an average temperature. Several positive pulses of higher temperature are observed at both the 1.5

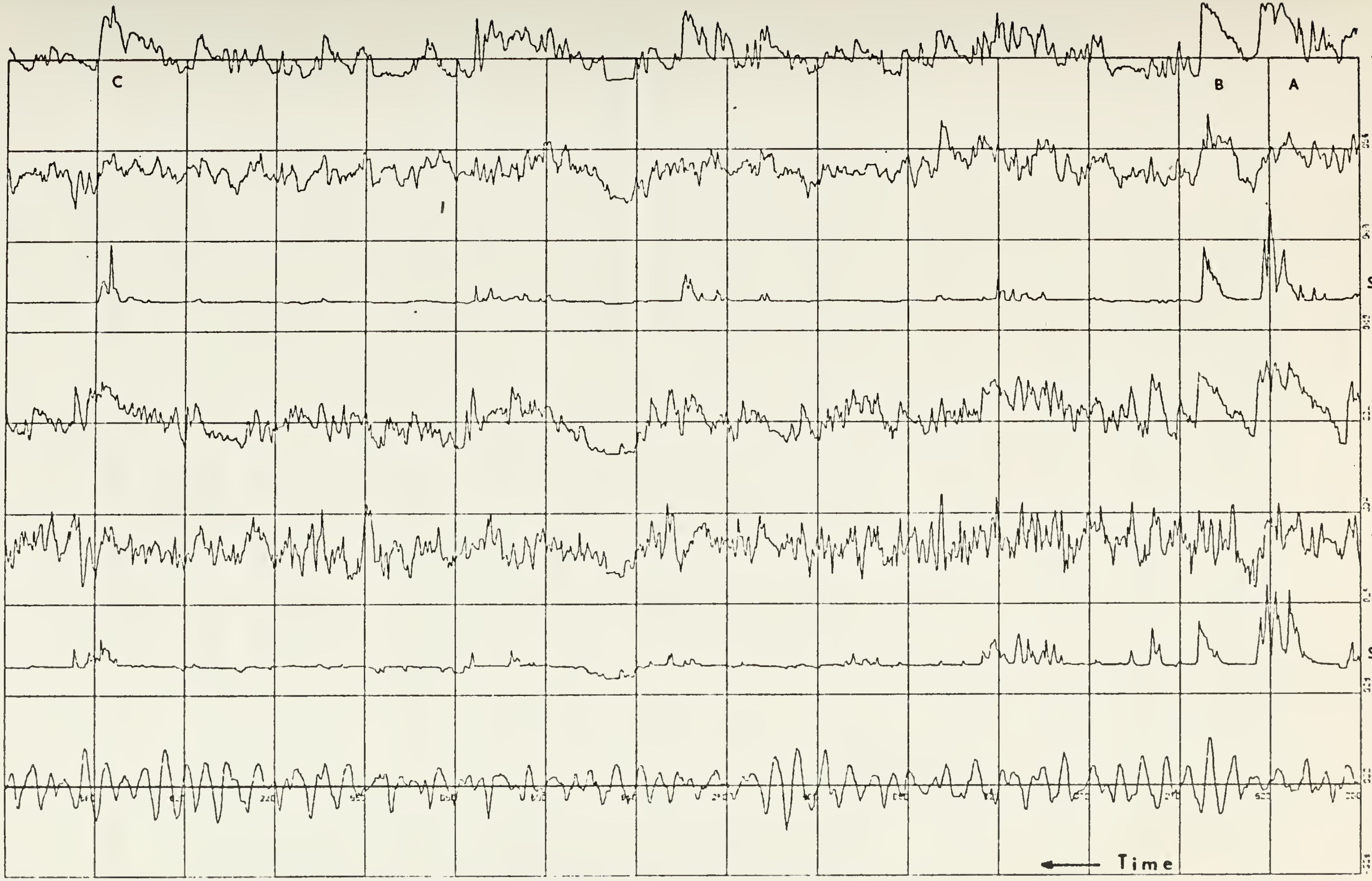

FIGURE 20. Simultaneous Traces of Variables Exhibiting Ramp-like Structures and Associated Temperature Drop.

and 4.0 meter levels and these are associated with micro-thermals. Taylor (1958) in describing a similar trace stated:

> ". . .the pulses of higher temperature appear on the record as asymmetrical triangular waves of temperature (gradual rise followed by sudden drop) and frequently attain several degrees in magnitude with duration mostly about 10-20 seconds. . .An interesting feature of the temperature traces is that there frequently seem to be a fairly constant 'base' temperature and temperature fluctuations which are almost exclusively positive related to it."

Note that the ramps illustrated in Figure 20 are about six seconds in duration.

In examining the velocity traces near Points A, B and C of Figure 20, several features are noteworthy. First, the vertical velocity tends to increase as the microfront is approached. Second, there is a definite drop in the vertical velocity component at the microfront which can be associated with an increase in the horizontal component of the velocity. Finally, the vertical velocity is greater at the upper level and tends to be more organized.

The examination of the micro-thermal and the associated microfront included consideration of the possible maintenance mechanism. According to Kaimal and Businger (1970) maintenance is related to active stretching along the microfront and strong convergence perpendicular to it. This is substantiated by the results of this study which revealed a sharp increase in the vertical velocity at the upper level and an increase in the horizontal velocity component preceding the microfront.

Additional simultaneous recordings at the 1.5 and 4.0 meter levels (in Appendix A) show that the micro-thermal can

be readily identified at both levels and hence the tilts are also visible. Considering Figure 20 we see that the tilt in the micro-thermals is in the downwind direction which is manifested by the arrival of the microfront at the upper level prior to that at the lower level.

The tilt of the micro-thermals was computed using two separate techniques. The first method utilized the balance proposed in the stretching mechanism wherein the tilt is a function of the u and w components of velocity at the two heights as described in Section IA. The second method related the tilt to the time lag between the arrival of the microfront at the upper level and that at the lower level and the mean translation velocities.

The first method produced an average tilt for all the micro-thermals of 52 degrees, whereas the average tilt computed by the second method was 56 degrees. These results are greater than published values of Kaimal and Businger (1970).

Table 1 lists general statistics computed for each of the three periods. For Period 5, 26 September (1100-1120), the micro-thermals accounted for 12 percent of the total length at the 1.5 meter level, but they accounted for 34 percent of the total heat flux. At the 4.0 meter level they accounted for 6 percent of the temperature trace, but 20 percent of the total flux. For Period 7, 26 September (1355-1415) at the 1.5 meter level micro-thermals accounted for 12 percent of the temperature trace, but accounted for 41 percent of the total heat flux. At the 4.0 meter level,

TABLE 1. Statistics on Structure and Heat Flux Associated with Observed Micro-thermals.

Period	$H_{1/3}$	Level	Z/L	Percent trace	Percent heat flux	Heat flux rate, R	$\overline{W}$ cm sec^{-1}	$\Delta\overline{W}$ cm sec^{-1}	$\overline{W}_A / \overline{W}_B$	$\Delta\overline{U}$	Average tilt, β	Translation velocity, U_T	Estimated level of U_T
5	48cm	1.5m	.013	12	23	3.74	43	33	1.6	30cmsec^{-1}	48^{o}	4.2 msec^{-1}	< .2m
		4.0	.026	6	20	4.07	68						
7	38	1.5	.041	12	41	4.98	46	55	2.2	40	54^{o}	3.7	.2m
		4.0	.064	9	38	6.27	101						
9	46	1.0	.013	12	38	3.81	46	40	2.1	30	53^{o}	2.9	.4m
		2.0	.016	8	23	3.33	76						

micro-thermals accounted for nine percent of the trace, but accounted for 38 percent of the total heat flux. In Period 9, 27 September (1140-1200), at the 1.0 meter level micro-thermals accounted for 12 percent of the trace, but accounted for 35 percent of the total heat flux, while at the 2.0 meter level micro-thermals accounted for eight percent of the trace, but accounted for 23 percent of the total heat flux.

B. EXAMINATION OF THE WAVES INFLUENCE

Kaimal and Businger (1970) and Taylor (1958) made use of measurements over flat land and many of their observations were verified in this study. For example, the description of the temperature and vertical velocity fluctuation indicated both upward and downward velocity fluctuation in areas of positive temperature fluctuations, at least in the lower level. The results agreed in the fact that the vertical velocity

was larger at the upper level than at the lower level. However, waves may also have had some influence on the micro-thermal occurrences in the present study. From previous discussion of wind-wave coupling it is evident that the waves do influence the airflow in the near surface layer. Unfortunately, only two types of influence could be substantiated by the analyses in this study.

First, the micro-thermals appeared to be associated with large wave trains. This association was substantiated solely on the basis of an examination of the strip chart recordings as shown in Appendix A. The large wave trains were either in the area of the micro-thermals or slightly downstream. The latter relationship may be due to the fact that the speed of the waves is greater than that of the airflow above the waves.

Second, the effect due to the vertical velocity of the wave surface can be examined by considering the derivative of the wave height in conjunction with the velocity structure at the 1.5 meter and 4.0 meter levels. Figure 21 depicts the temperature and velocity fluctuations in the area of two micro-thermals with the associated derivative of the wave height field. A comparison of the derivative of the waves (essentially the vertical velocity of the wave surface) and the vertical velocity field at 4.0 meters does not show a close correlation. This could be due to the fact that buoyant acceleration is increasing the vertical velocity of the parcel as it rises. At the 1.5 meter level, however, there

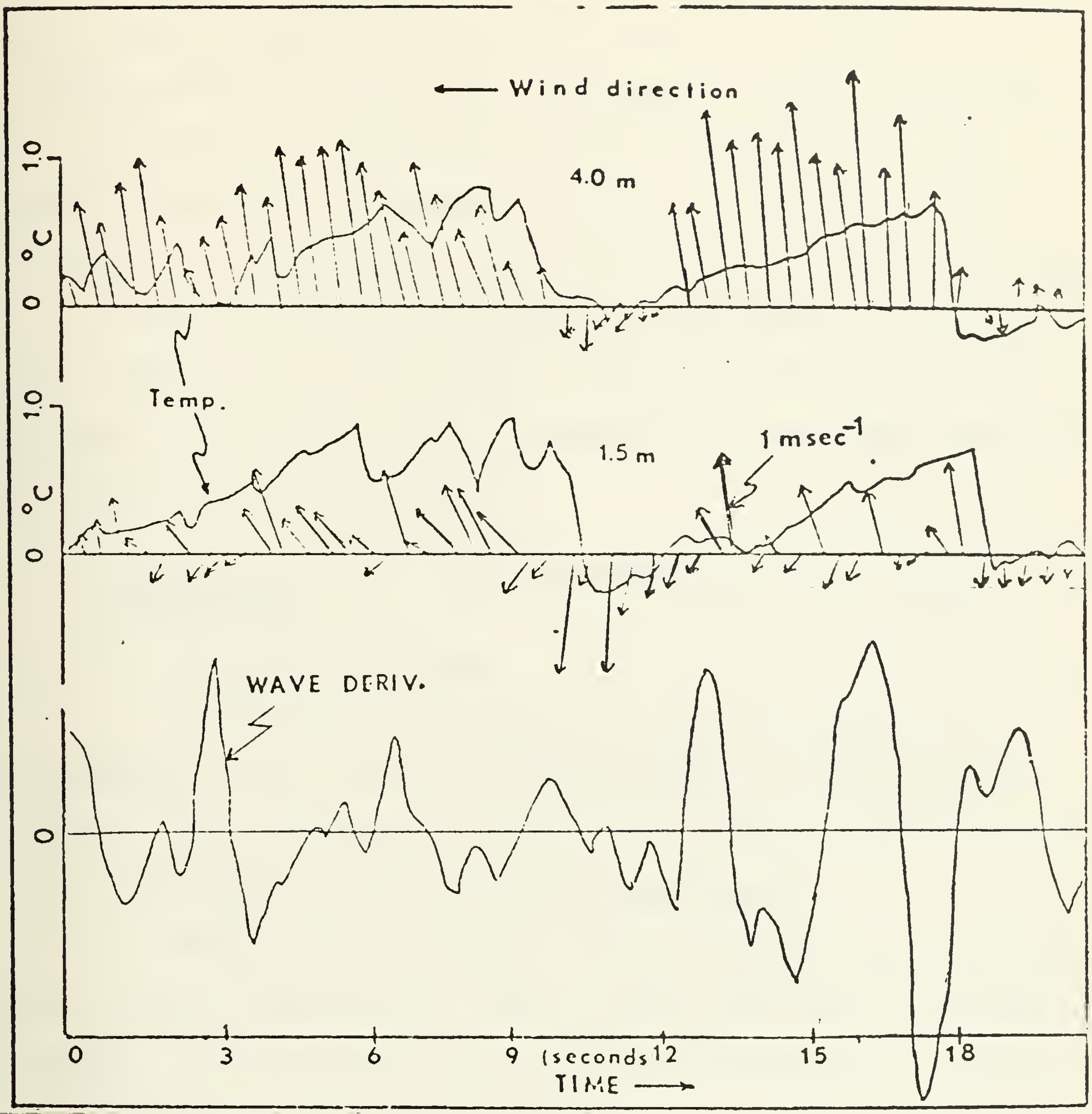

FIGURE 21. Temperature and Velocity Fluctuations above the Derivative of the Wave Height Field.

appears to be a correlation between the vertical velocity structure of the waves and the vertical velocity at 1.5 meters. The area of downward vertical velocity at 1.5 meters is superimposed over the area of the waves' downward velocity.

Therefore, although the vertical velocity within the micro-thermal at 4.0 meters is upward, as expected in the convective mechanism, the vertical velocity at the lower level (1.5 meters) definitely reflects the influence of the waves. The observations are, perhaps, evidence for Gibson's (1971) suggestion that the vortice mechanism is responsible for the origin of the micro-thermals.

C. APPLICATION TO HEAT FLUX ESTIMATES AND OPTICAL WAVE PROPAGATION

1. Heat Flux Estimates

As discussed in Section IV-A, micro-thermals are responsible for a significant percentage of the total heat flux. This conclusion is important in view of recent results and investigations of over-water measurements.

Phelps and Pond (1971) analyzed temperature, humidity and velocity fluctuations observed near San Diego and during BOMEX[3]. Both of these sets of data contained micro-thermals.

[3]The BOMEX experiment was a joint investigation of several agencies and universities for the purpose of establishing the energy budget of an atmospheric volume 500 km on a side and about 5 km high. The volume was located in the Trade Wind region of the Atlantic Ocean. These data represent measurements from 2 to 8 meters above the surface near the center of the volume (in the vicinity of 14 N latitude and 57 W longitude). A majority of these data were from simultaneous measurements of both velocity and temperature fluctuations at two levels. The measurements were made from the Scripps Institute of Oceanography Floating Instrument Platform (FLIP).

From these investigations Phelps and Pond concluded:

> ". . .that the temperature spectra and w't cospectra do not have universal forms in the sense of the Monin-Obukhov similarity theory over the frequency range which provides the main contributions to sensible heat flux. Similarity theory does not provide for radiation affects. The theory will only work when such effects are small such as in temperate latitudes where the absolute humidity is usually fairly low over both land and sea. . ."

Phelps and Pond (1971) suggested that the bulk aerodynamic formulae method for predicting sensible heat flux is inadequate. Although radiation could be a factor on the heat flux, as suggested above, it appears that the micro-thermals should have also been considered as contributors to the total heat flux. Based on the results of the present study, approximately 10 percent of a 20 minute period was occupied by micro-thermals but accounted for 32 percent of the total heat flux. Bulk aerodynamic methods of computing sensible heat flux are based on exchange coefficients and these coefficients have been empirically determined from observations in a fully turbulent regime over land. With occurrences of micro-thermals, due in part to the waves' influence, coefficients obtained over land are probably inappropriate for over-water analyses.

2. Optical Wave Propagation

Another important applied problem is the description of the near surface layer for optical propagation. To predict the path and the scintillation of optical wave propagation, a refractive index constant must be computed. Although the micro-thermals represent a small part of each record, roughly

ten percent, they do represent large horizontal temperature discontinuities. A typical value of the horizontal micro-front temperature gradient is 0.17° C per meter. Since most uses of optical wave propagation would be in the horizontal direction, during unstable situations the presence and vertical extent of these micro-thermals should be taken into account.

It is noted that present estimates on the properties of the surface layer with respect to optical wave propagation are based only on stability parameters, therefore observations of possible wave influences on the structure and occurrence of the micro-thermals are ignored. In order to improve the ability to predict optical wave propagation, further studies relating the waves' influence are needed.

V. SUMMARY AND CONCLUSIONS

Turbulence data obtained in the airflow adjacent to waves were examined for information on the occurrence and importance of micro-thermals. Analysis procedures were selected or developed to:

1. identify the occurrence of micro-thermals in the temperature and velocity records,

2. determine if features in the corresponding velocity fluctuations were similar to those observed by Kaimal and Businger and which suggest the 'stretching mechanism',

3. determine the relative importance of the micro-thermals for sensible heat flux and

4. determine the relative influence of thermal stratification and wind-wave coupling on the occurrence and features of the micro-thermals.

On the basis of the results obtained and interpretations presented from these analyses and from a limited sample of data, the following conclusions are made:

1. The skewness of the temperature fluctuations appears to be a good statistic for delineating the micro-thermals.

2. The agreement between the tilts computed from the vector balance and tilts computed from lags and mean wind speed indicated that the observed microfront were maintained by buoyant 'stretching'. The relative increase of the vertical component with height also supports a conclusion that buoyant acceleration is responsible for the structure and extent of the micro-thermals.

3. The micro-thermals account for a significant portion of the total sensible heat transfer. They represent about ten percent of the time interval and account for about 30 percent of the net sensible heat transfer. They also transfer sensible heat at a rate four to five times greater than the transfer rate in the ambient turbulence.

4. Although the maintenance and vertical extent of the micro-thermals appear to be due to buoyant accelerations and hence the thermal stratification it is suggested that they are initially formed near the surface by wave related motions. This suggestion is based on the observations that, in a given period, the micro-thermals appear in conjunction with large wave trains, that the period with the highest wave had the largest number of micro-thermals and that the velocity fluctuations at a lower level reflected the influence of the waves even in the micro-thermal. Also, velocity spectra for these periods reflected significant wave influence on the airflow.

The description of the micro-thermals and the above conclusions are relevant to several applied problems. Two of these are (1) estimating sensible heat transfer from a wave surface and (2) predicting optical wave propagation characteristics.

Future work should include an examination of over wave data from near neutral conditions. Decreasing the influence of the thermal stratification would enable the waves' influence to be examined more closely.

APPENDIX A

FIGURES 22-27: Successive Strip Charts for Period 5, 26 September 1968 (1100-1120). Three minute time frames depicting N, S/S, W, and T for 1.5 meters and S/S, W, and T for 4.0 meters.

FIGURES 28-33: Successive Strip Charts for Period 7, 26 September 1968 (1355-1415). Three minute time frames depicting N, S/S, W, and T for 1.5 meters and S/S, W, and T for 4.0 meters.

FIGURES 34-39: Successive Strip Charts for Period 9, 27 September 1968 (1140-1200). Three minute time frames depicting N, S/S, W, and T for 1.0 meters and S/S, W, and T for 2.0 meters.

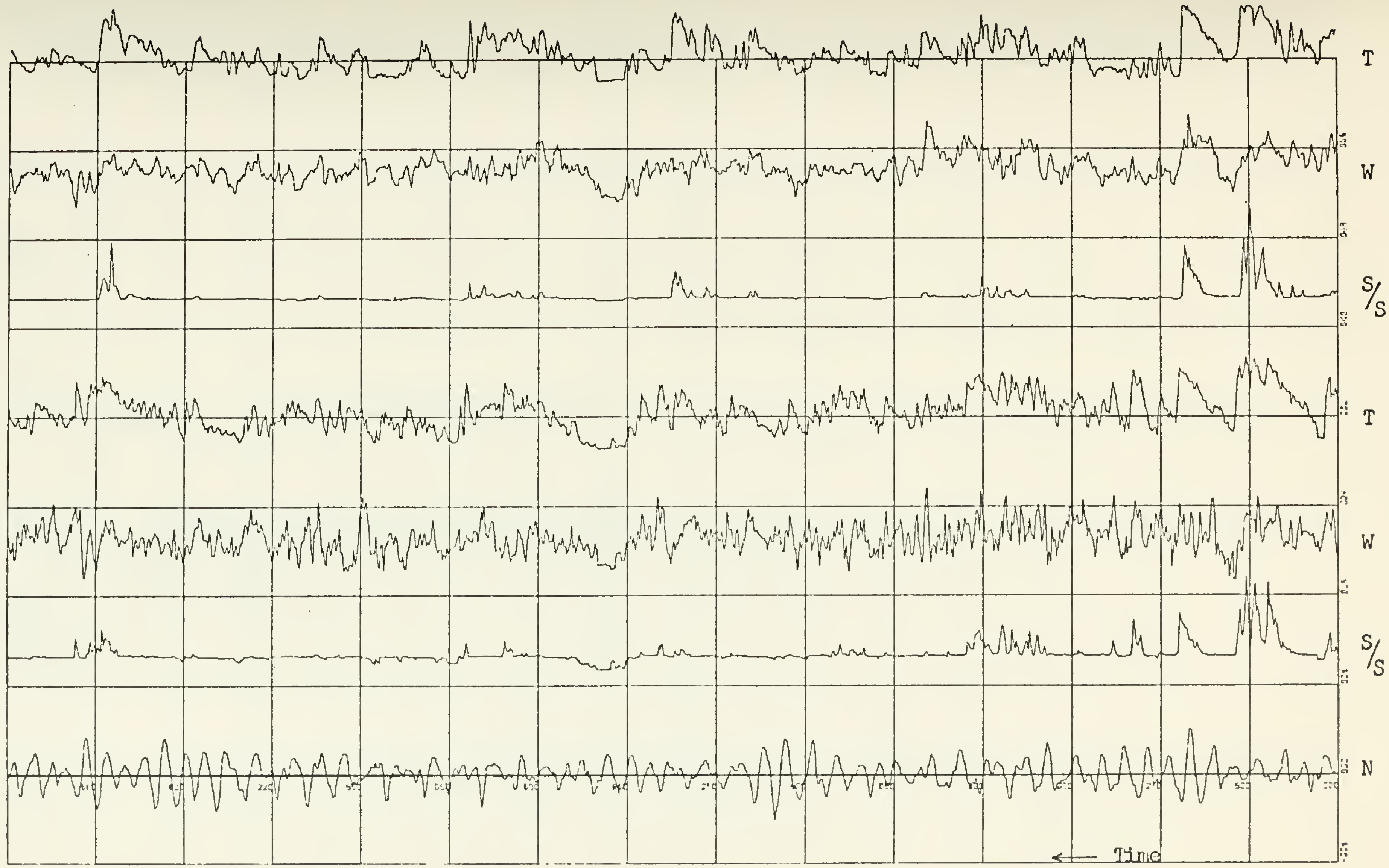

FIGURE 22. 1100 - 1103 Strip chart Period 5.

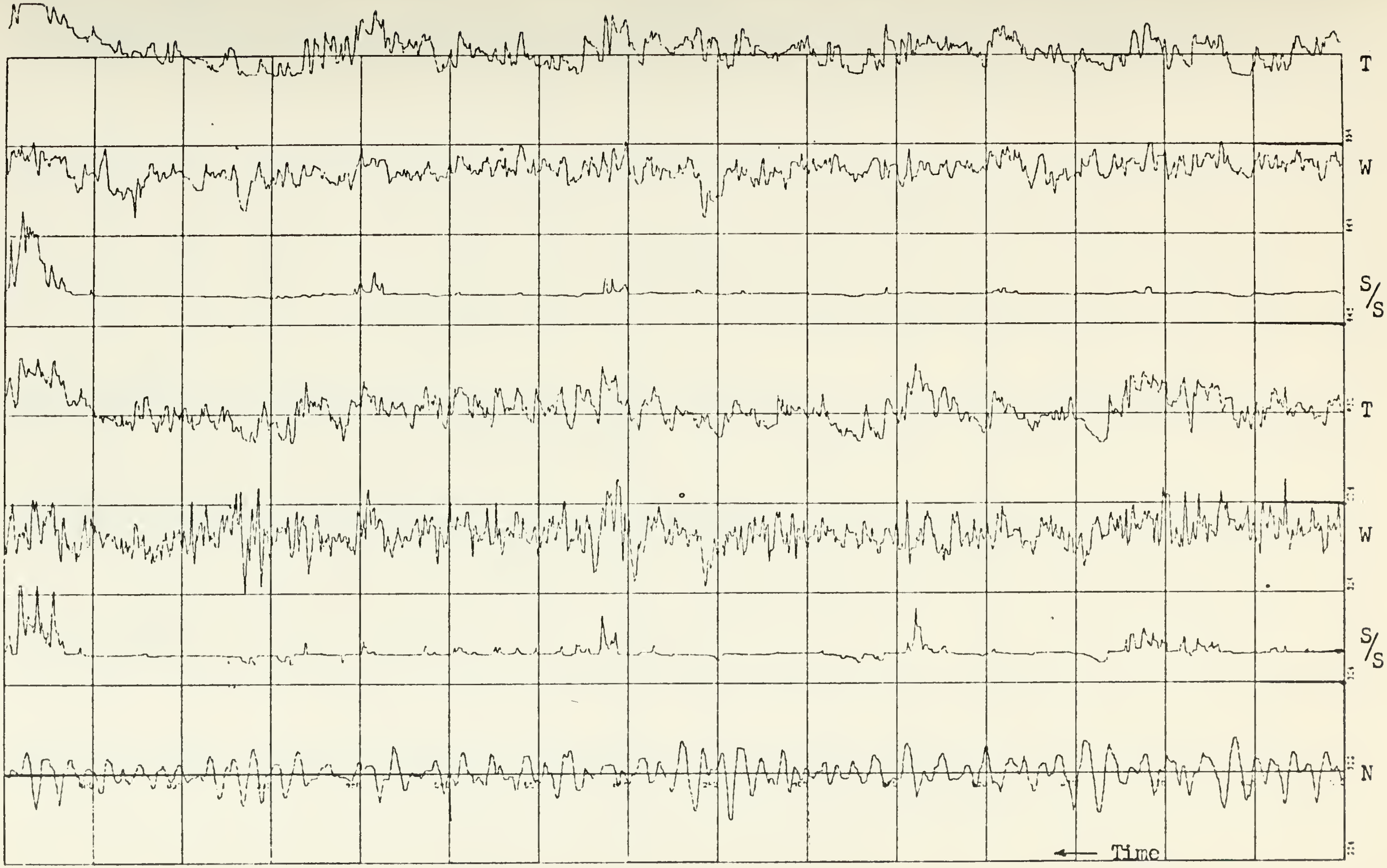

FIGURE 23. 1103 - 1106 Strip Chart Period 5.

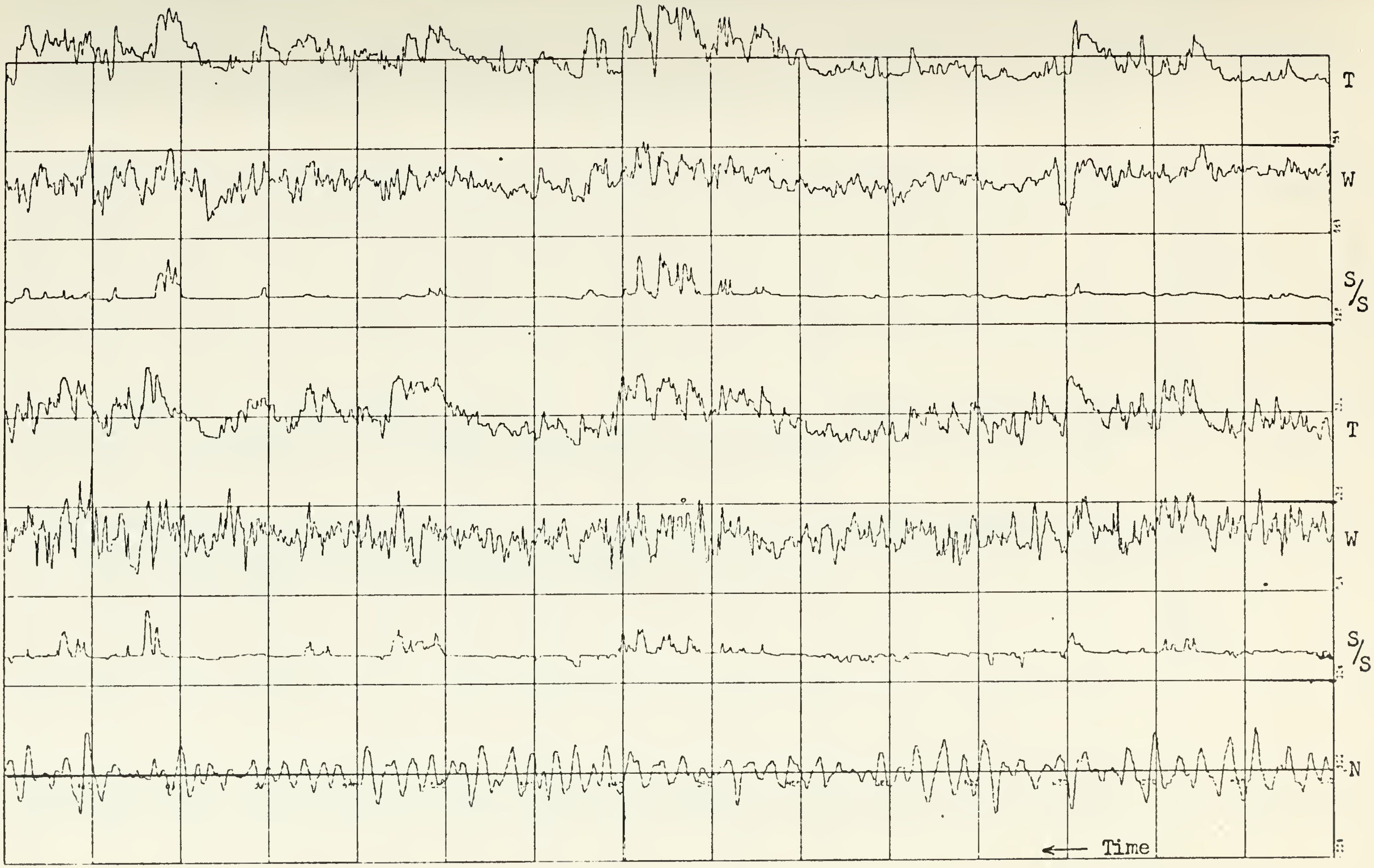

FIGURE 24. 1106 - 1109 Strip Chart Period 5.

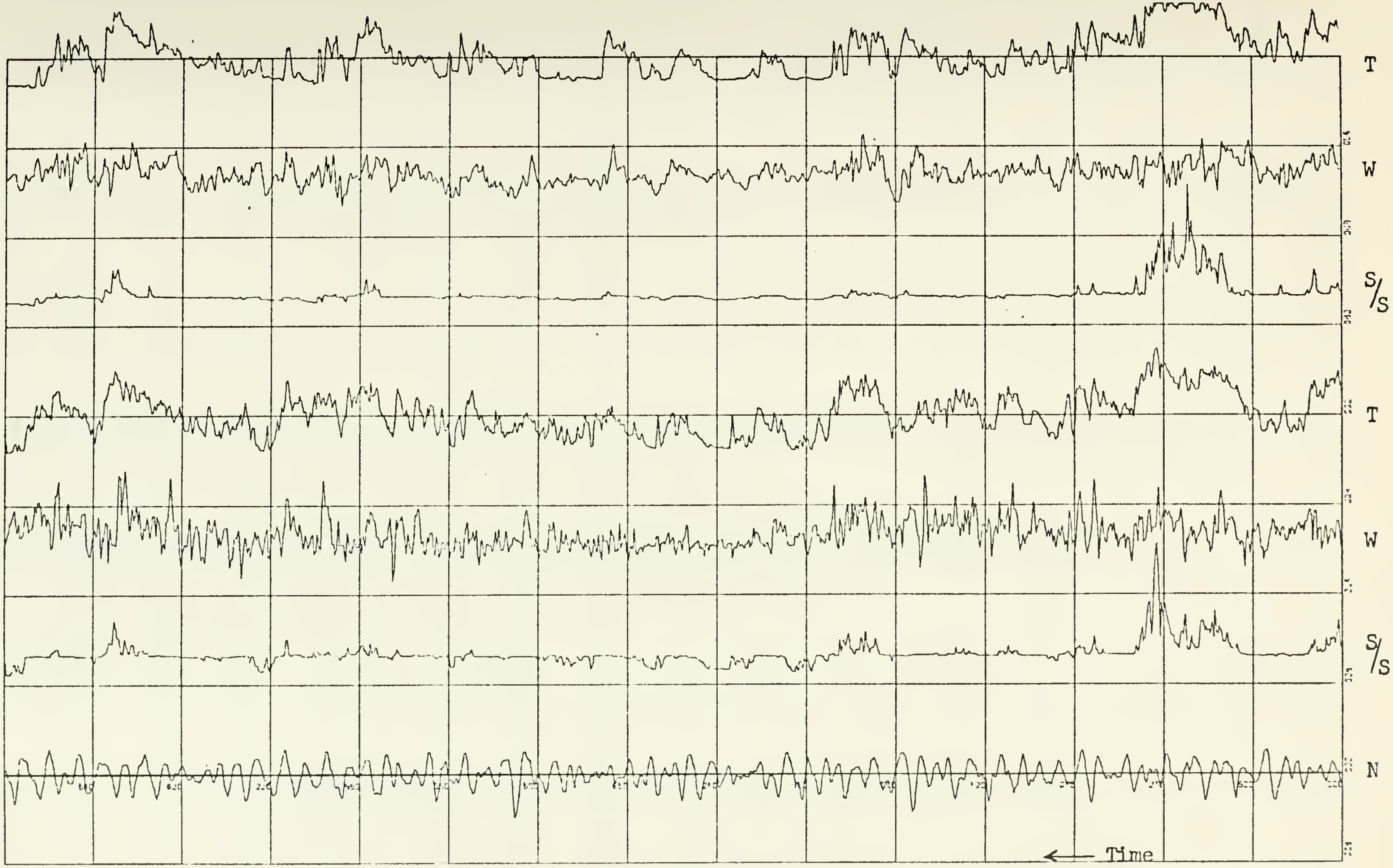

FIGURE 25. 1109 - 1112 Strip Chart Period 5.

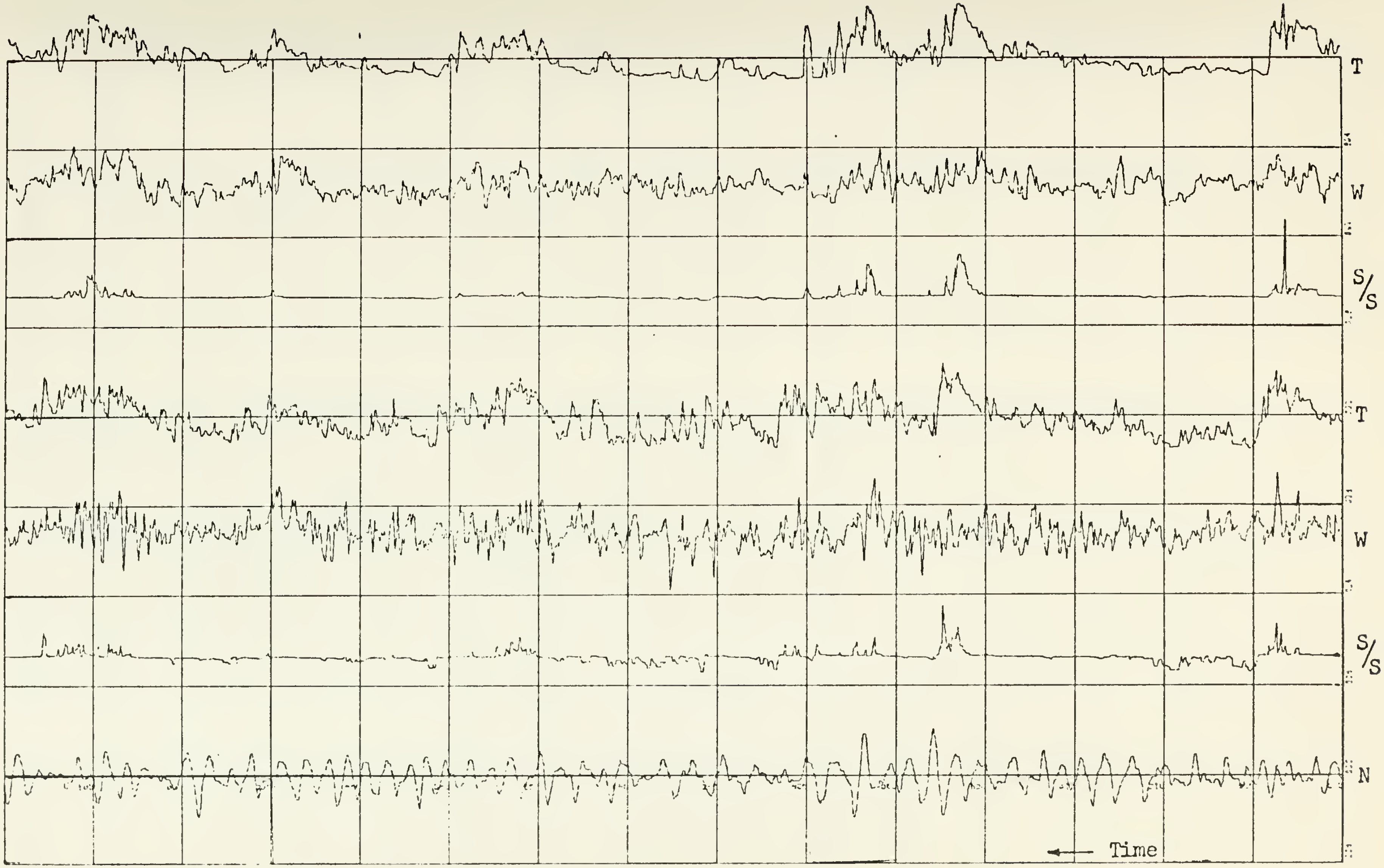

FIGURE 26. 1112 - 1115 Strip Chart Period 5.

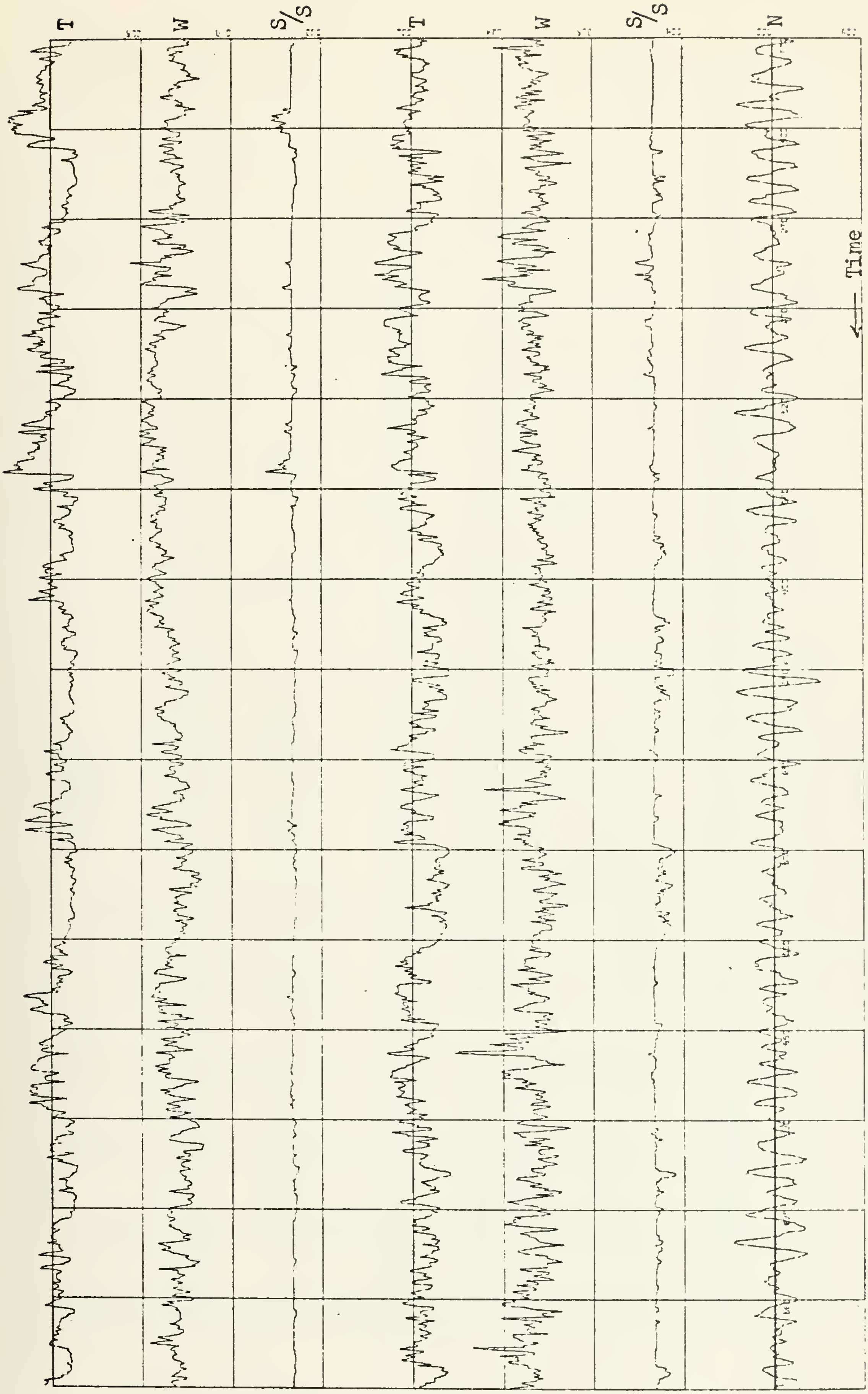

FIGURE 27. 1115 - 1118 Strip Chart Period 5.

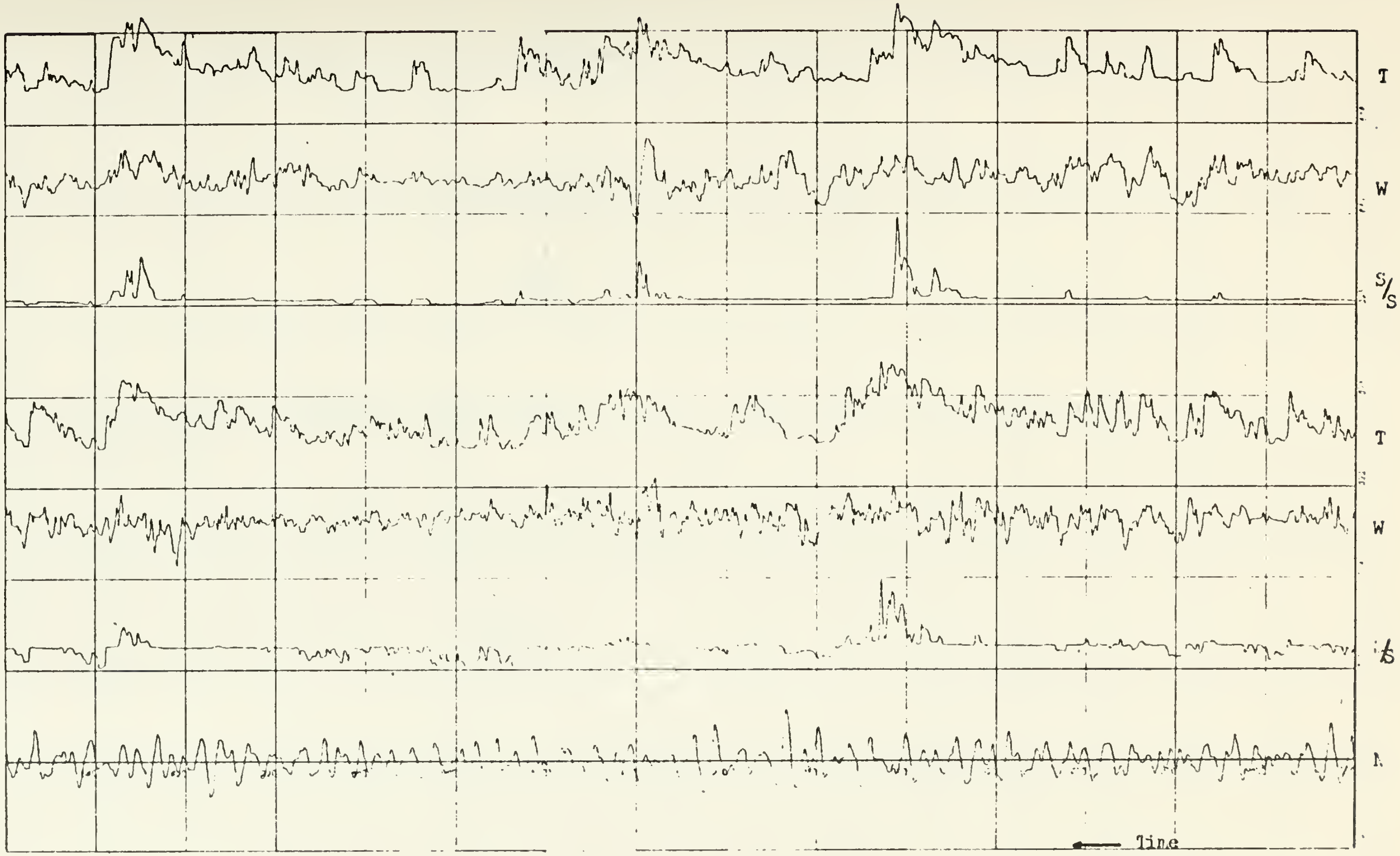

FIGURE 28. 1355 - 1358 Strip Chart Period 7.

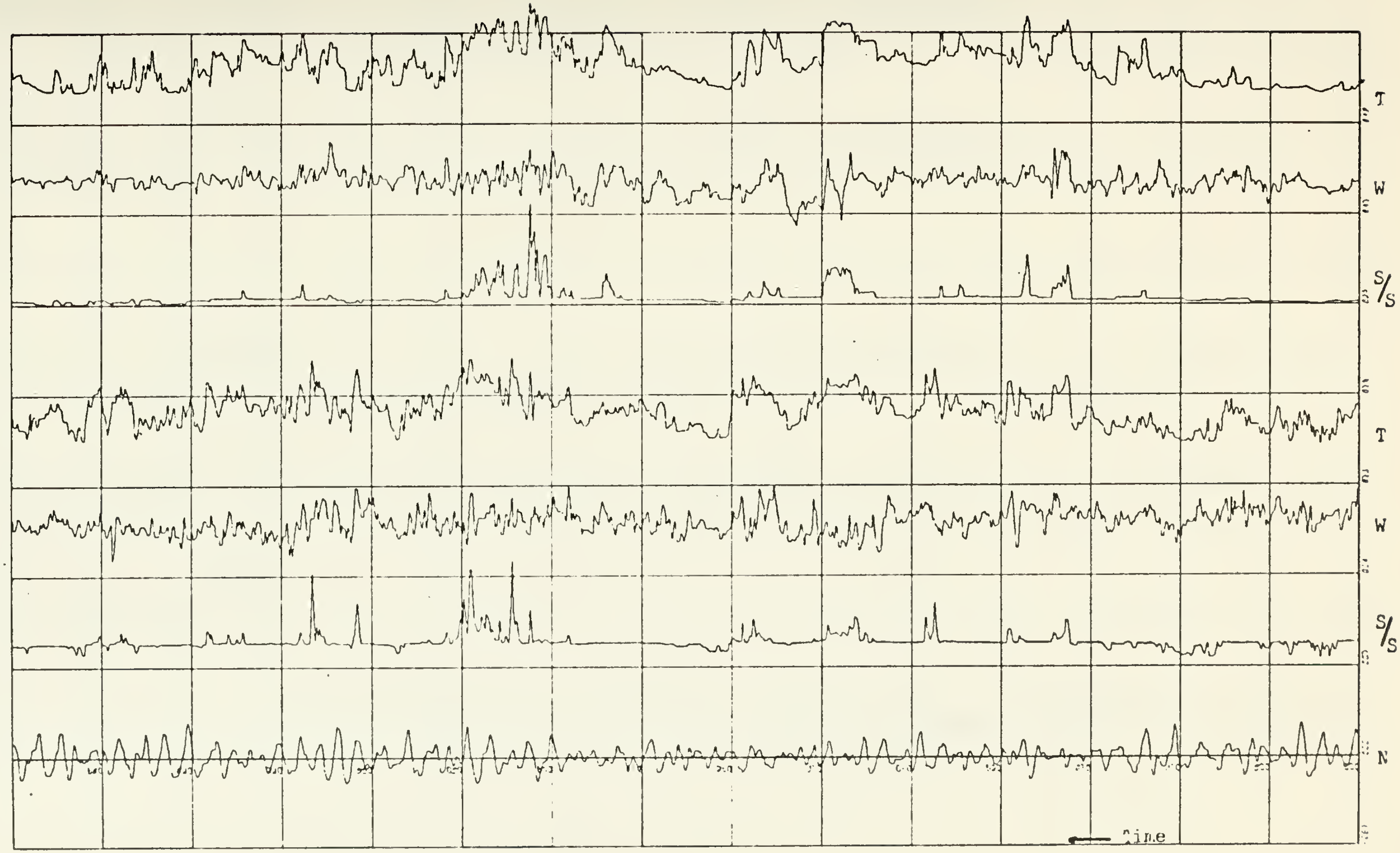

FIGURE 29. 1358 - 1401 Strip Chart Period 7.

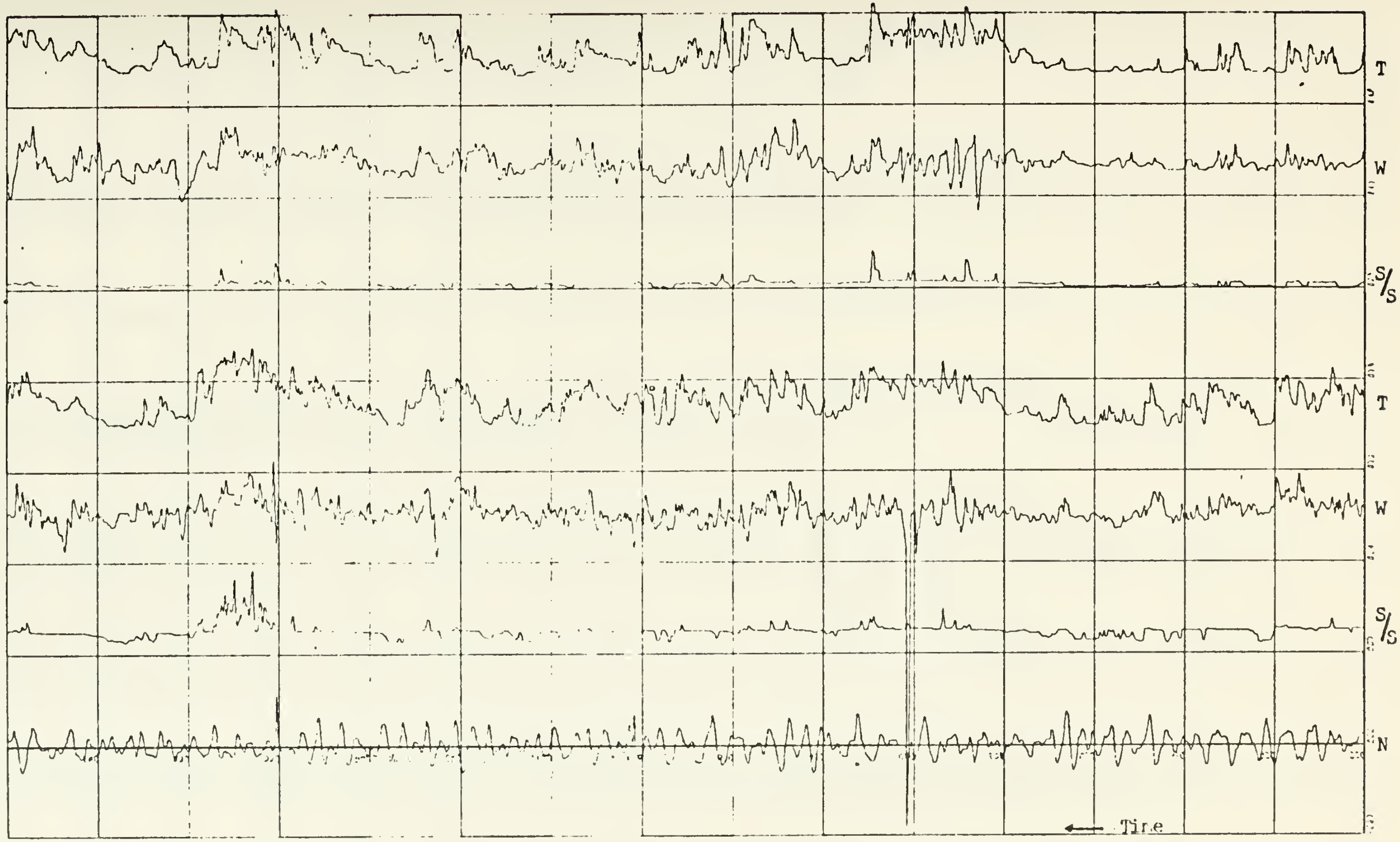

FIGURE 30. 1401 - 1404 Strip Chart Period 7.

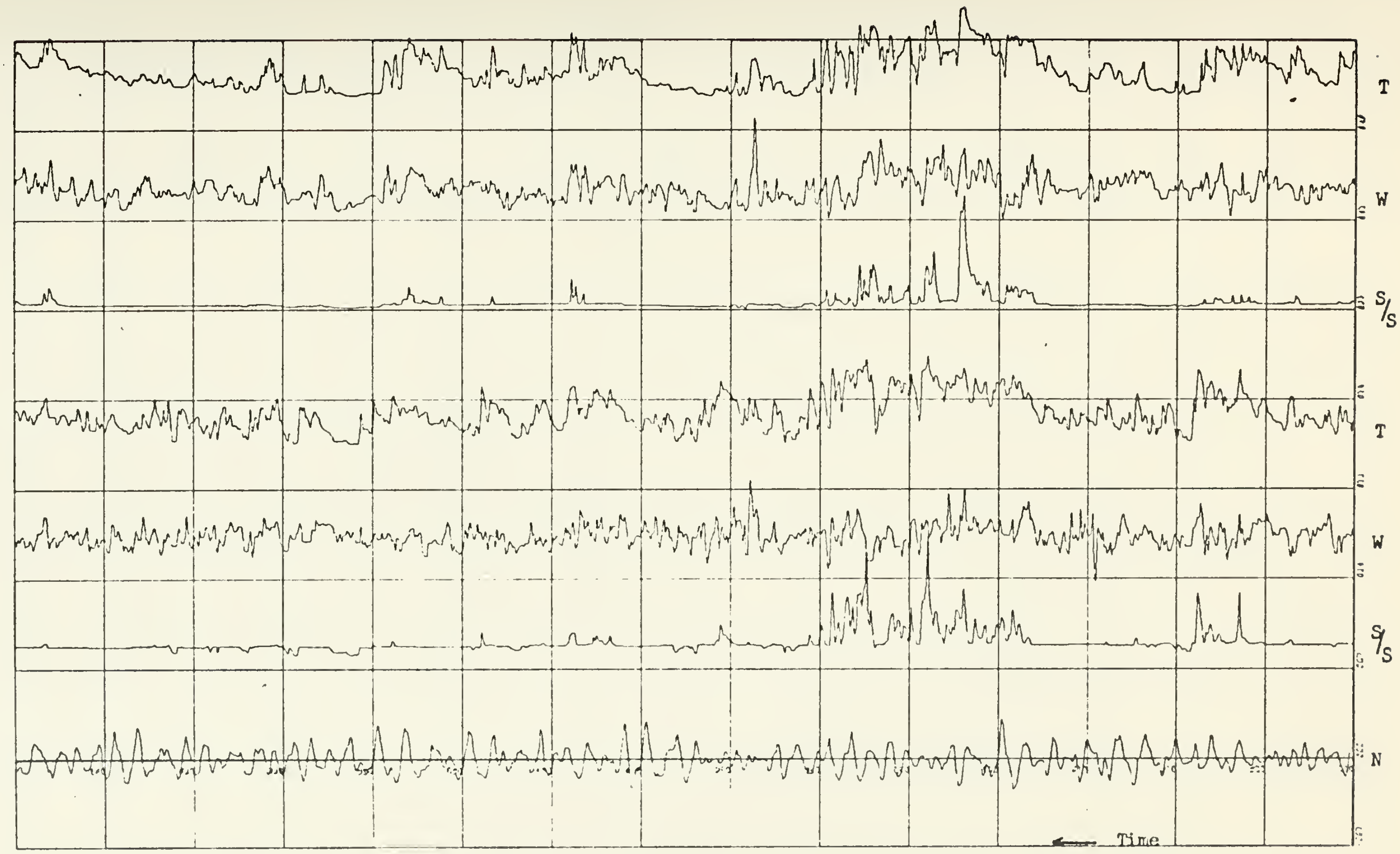

FIGURE 31. 1404 - 1407 Strip Chart Period 7.

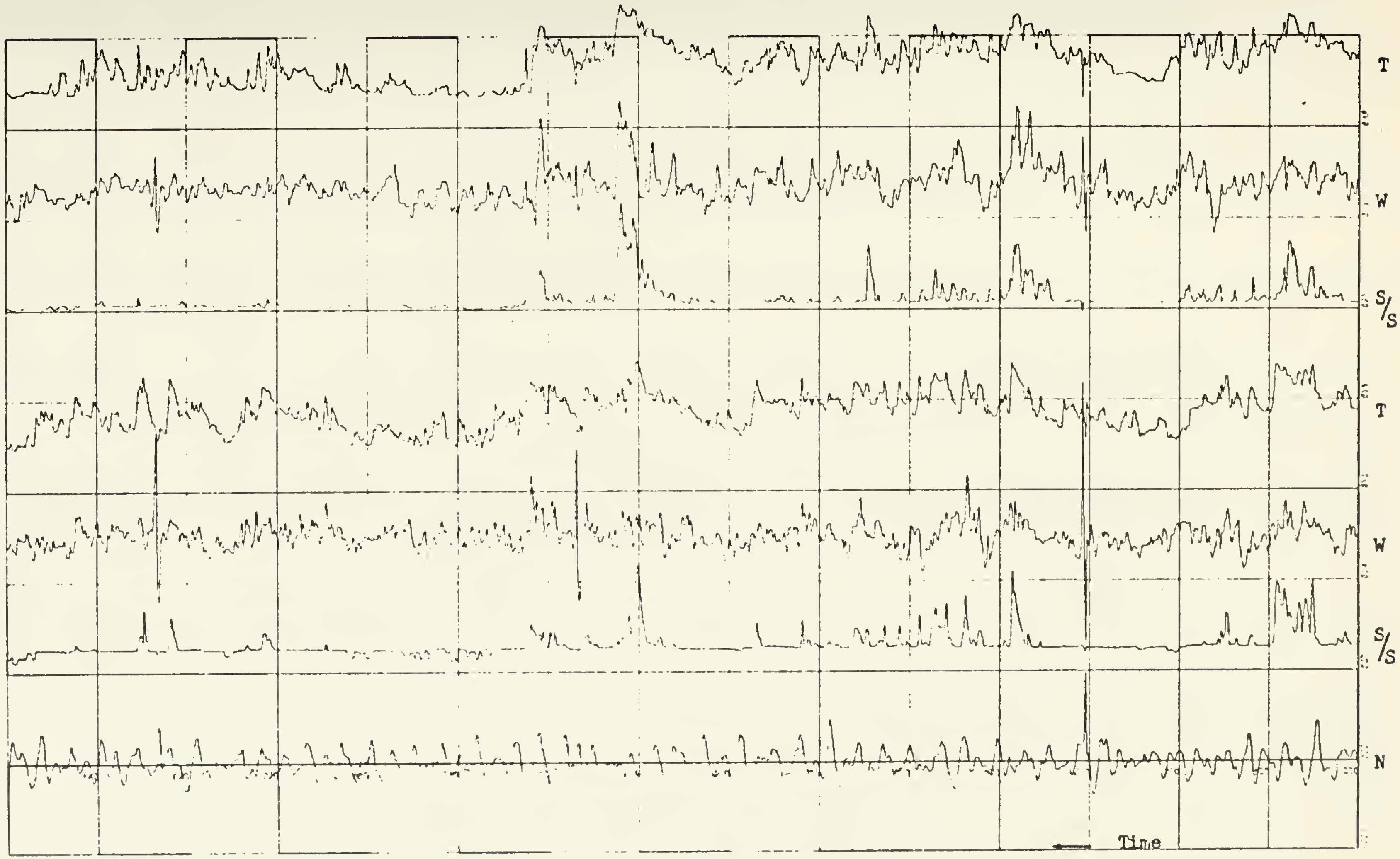

FIGURE 32. 1407 - 1410 Strip Chart Period 7.

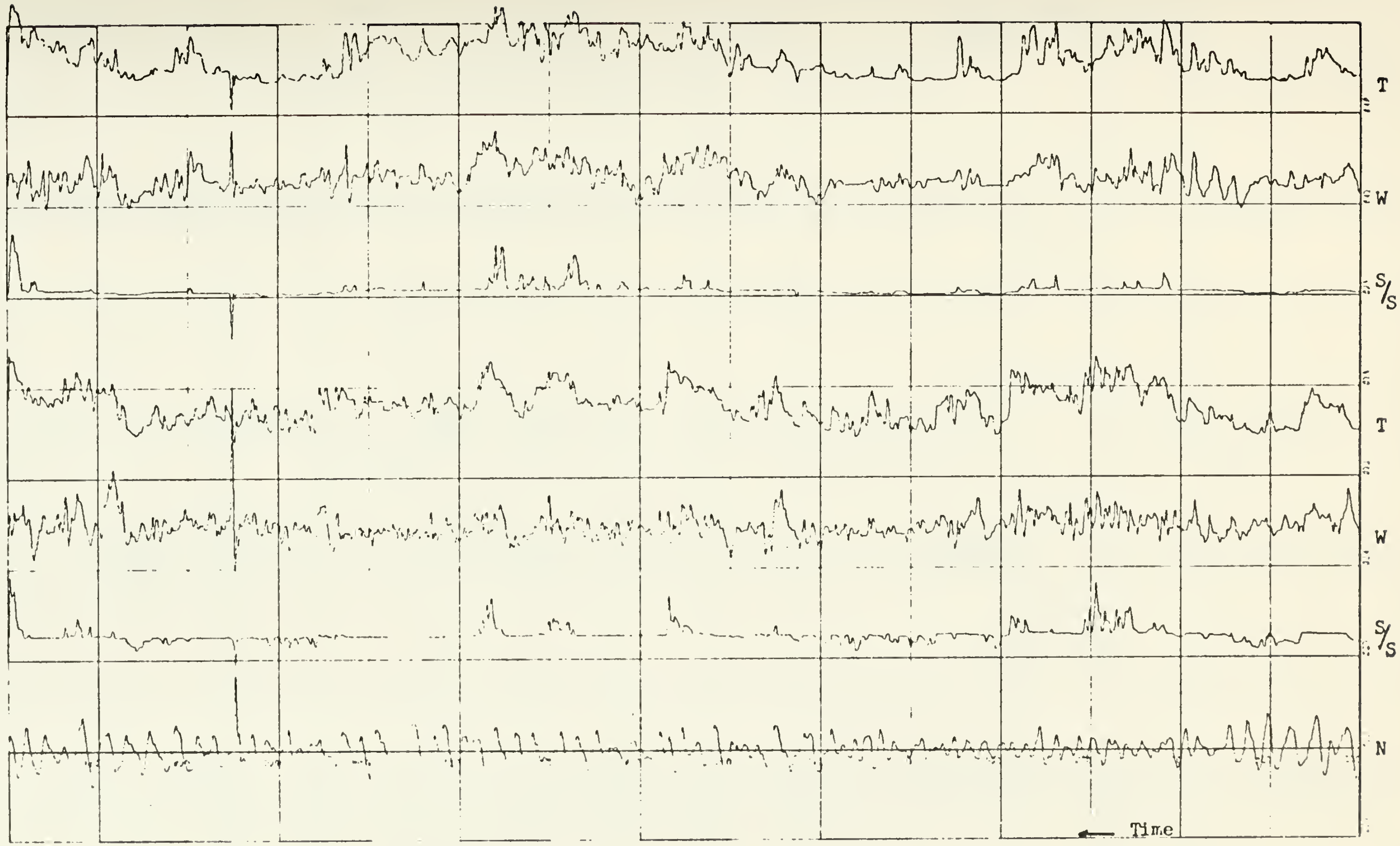

FIGURE 33. 1410 - 1413 Strip Chart Period 7.

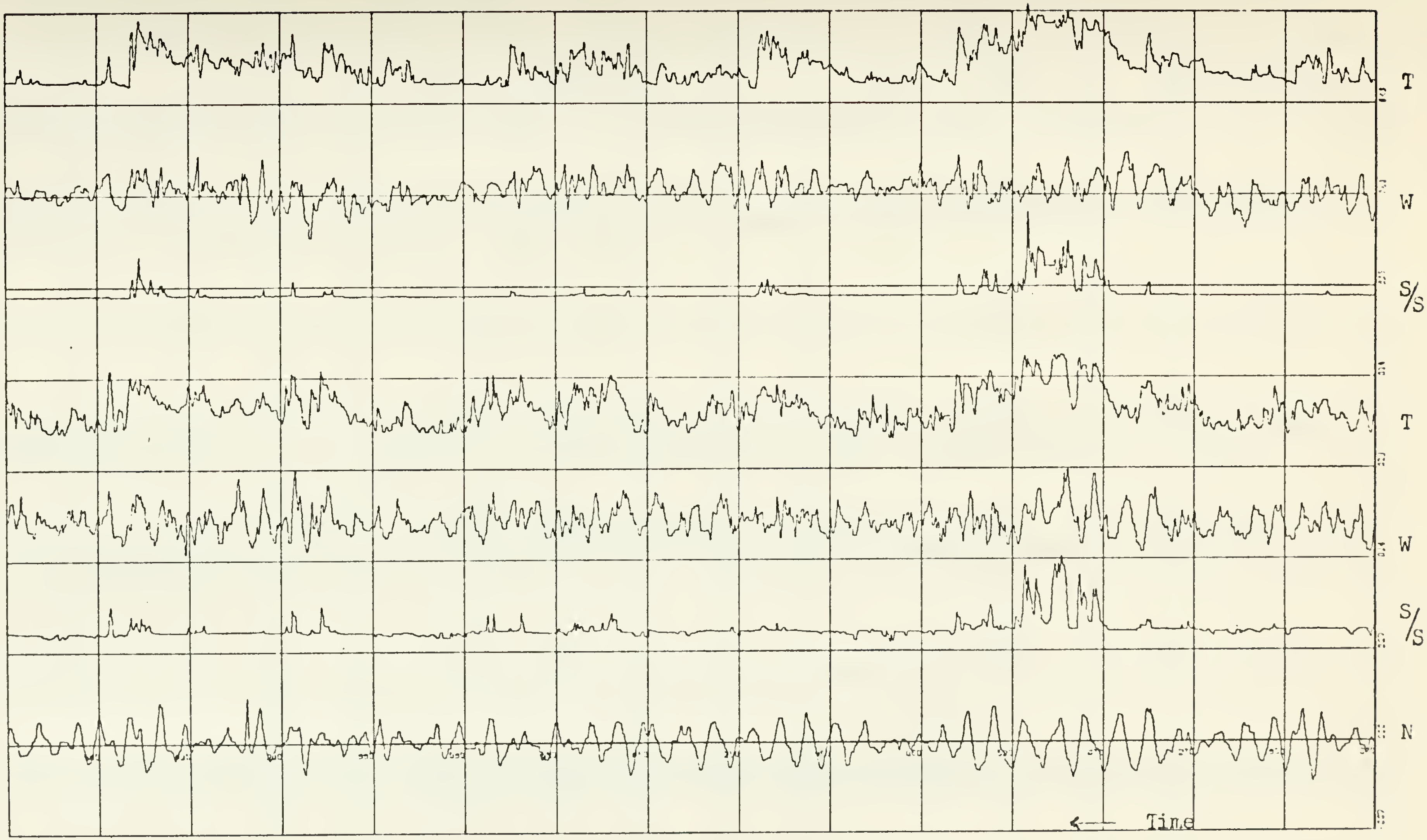

FIGURE 34. 1140 - 1143 Strip Chart period 9.

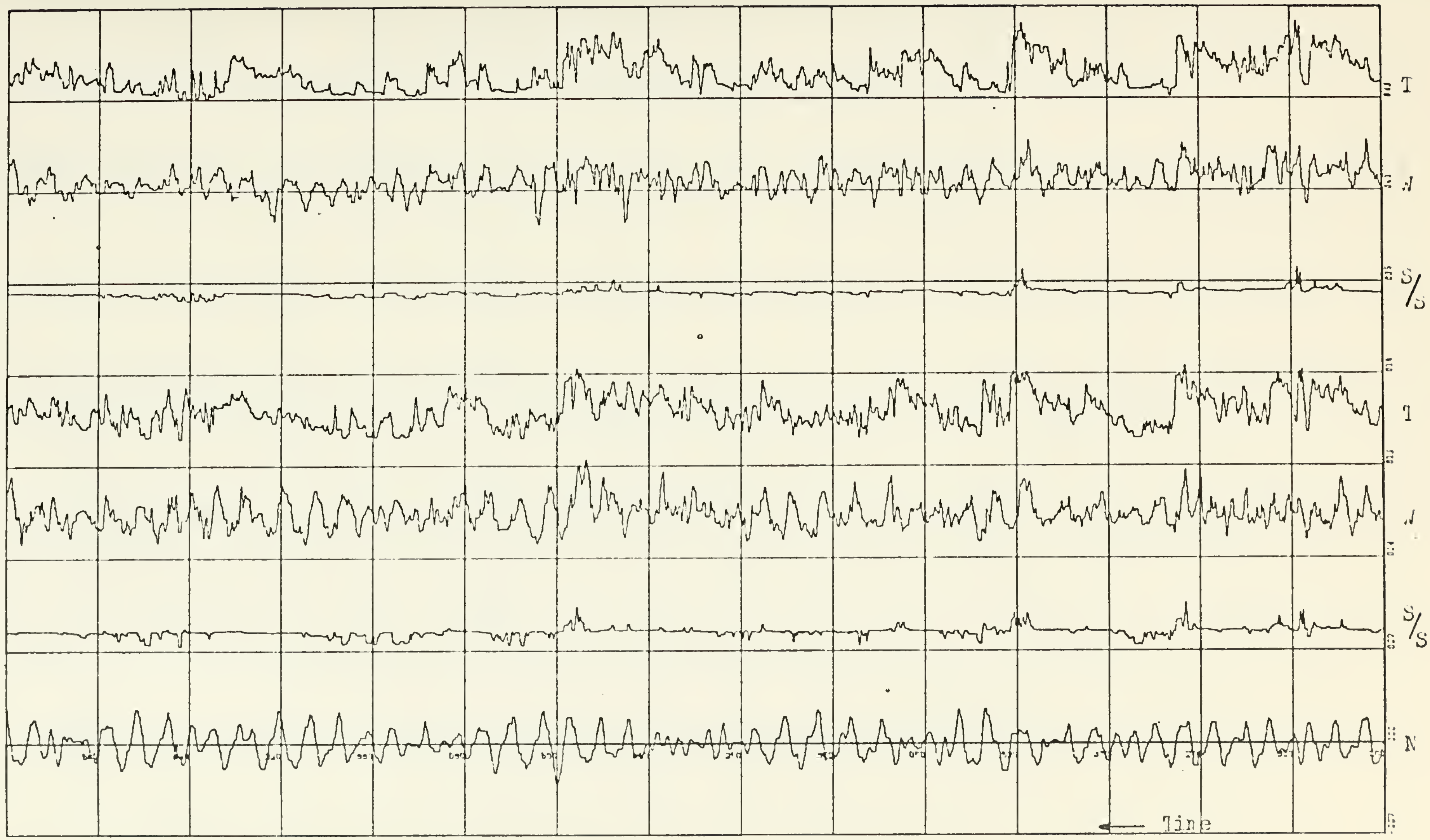

FIGURE 35. 1143 - 1146 Strip Chart Period 9.

FIGURE 36. 1146 - 1149 Strip Chart Period 9.

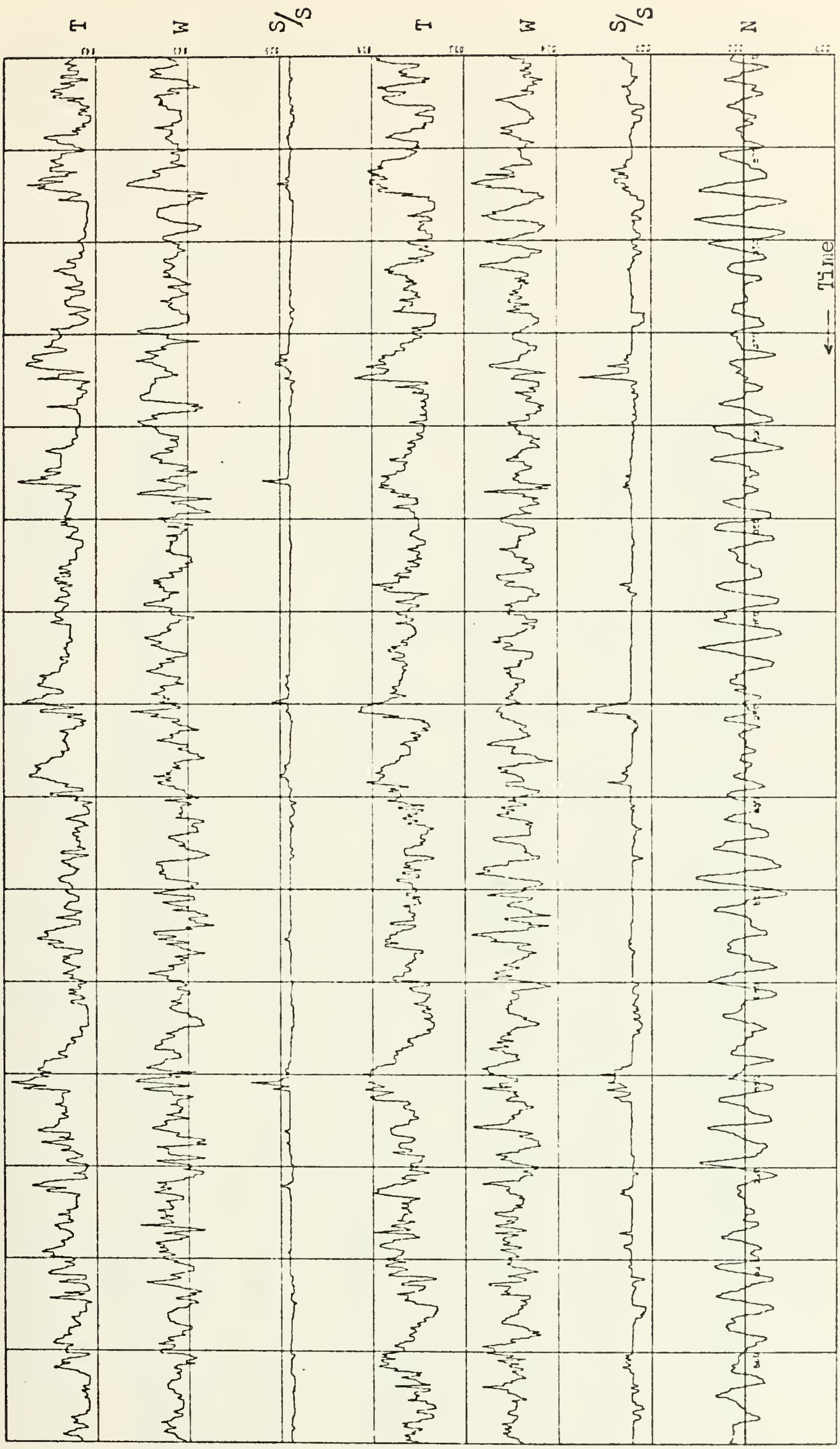

FIGURE 37. 1149 - 1152 Strip Chart Period 9.

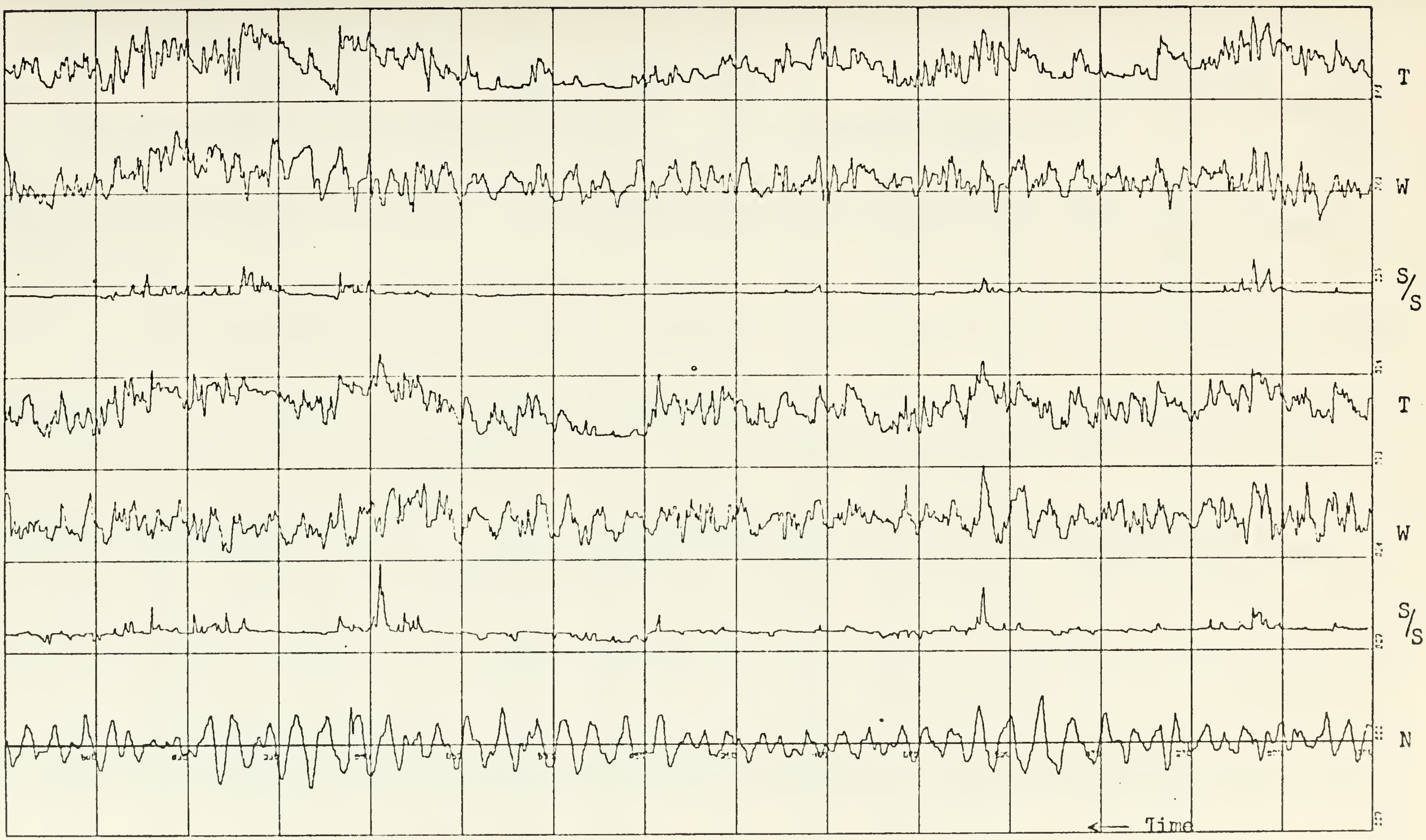

FIGURE 38. 1152 - 1155 Strip Chart Period 9.

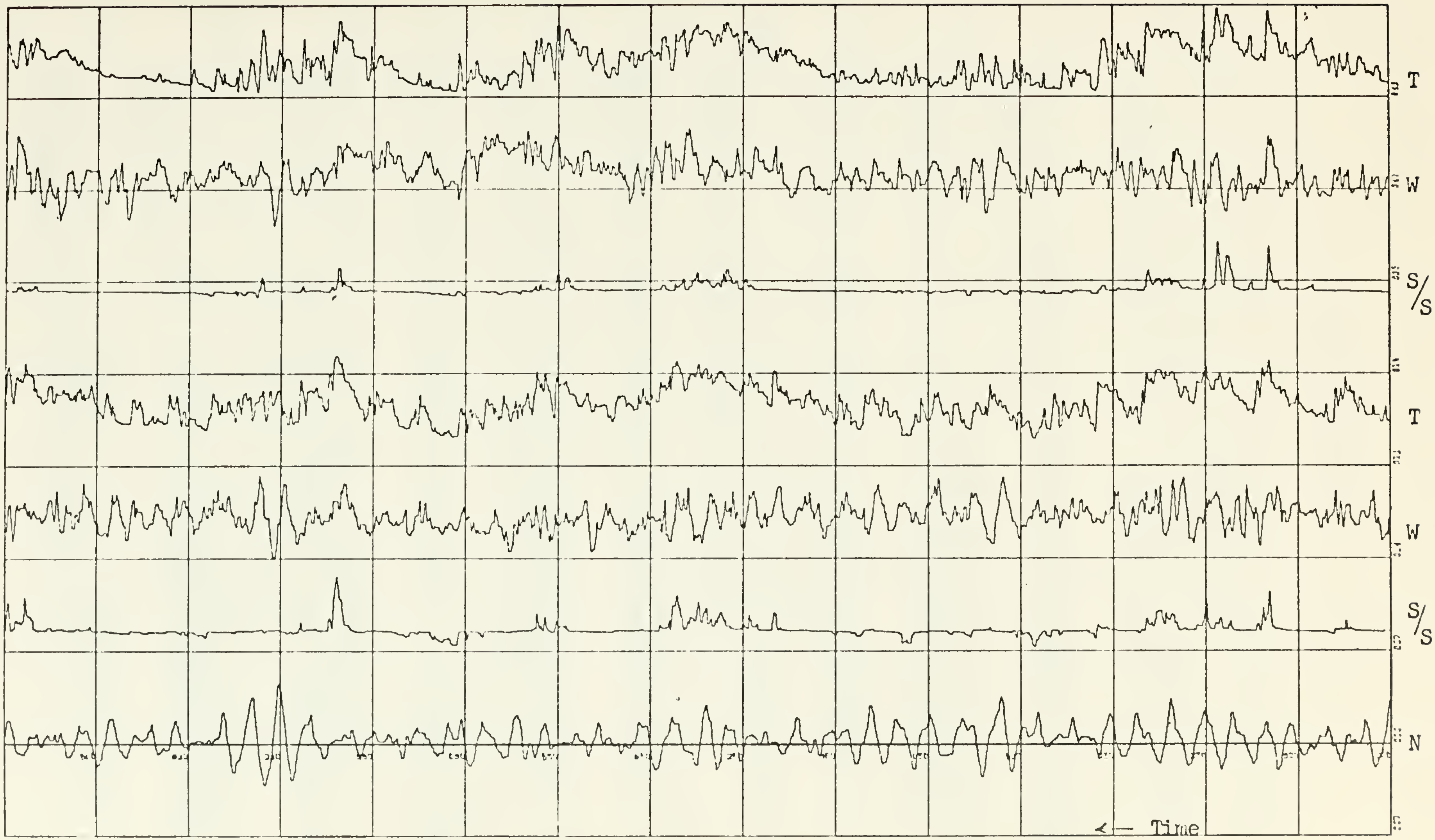

FIGURE 39. 1155 - 1158 Strip Chart Period 9.

BIBLIOGRAPHY

1. Barcilon, A. I., 1967: A Theoretical and Experimental Model for a Dust Devil. J. Atmos. Sci., 24, pp. 453-466.

2. Busch, N. E. and Panofsky, H. A., 1968: Recent Spectra of Atmospheric Turbulence. Quart J. Roy. Met. Soc., 94 (400), 132-149.

3. Coulman, C. E. and Hall, D. N. B., 1967: Optical Effects of Thermal Structure in the Lower Atmosphere. Applied Optics, 6, pp. 497-504.

4. Davidson, K. L., 1970: An Investigation of the Influence of Water Waves on the Adjacent Airflow. ONR Contract No. N000 14-67-A-0181-0005, University of Michigan.

5. Davidson, K. L. and Frank, A. J., 1971: Properties of Wave-Related Fluctuations in the Airflow above Natural Waves, Submitted J. Phy. Ocean. 21 p.

6. Elder, F. C., D. L. Harris and A. Taylor, 1970: Some Evidence of Organized Flow over Natural Waves, Boundary Layer Meteorology, 1, 80-87.

7. Gibson, C. H., Friehe, C. A., and McConnell, S. D., 1971: Measurements of Sheared Turbulent Scalar Fields. AGARD Fluid Dynamics Panel.

8. Gill, T. E., 1971: Analysis of Temperature and Velocity Fluctuations in the Atmospheric Boundary Layer. Master's Thesis, Naval Postgraduate School, 57 p.

9. Kaimal, J. E. and Businger, J. A., 1970: Case Studies of a Convective Plume and Dust Devil. J. Appl. Meteor. 9(4), 612-620.

10. Karaki, S. and E. Y. Hsu, 1968: An Experimental Investigation of the Structure of a Turbulent Wind over Water Waves. Technical Report No. 68, Department of Civil Engineering, Stanford University, 100 pp.

11. Kitaygorodskii, S. A., 1969: Small-Scale Atmosphere-Ocean Interaction, Izv., Atmospheric and Oceanic Physics, 1969, Vol. 5, No. 11, pp. 1114-1131, Translated by Kenneth Syers.

12. Lai, R. J. and O. H. Shemdin, 1971: Laboratory Investigations of Air-Turbulence above Simple Water Waves. J. Geophys. Res., 76, 7334-7350.

13. Miles, J. W., 1957: On the Generation of Surface Waves by Shear Flows, J. Fluid Mech., 3, 185-204.

14. Morton, B. R., G. I. Taylor and J. S. Turner, 1956: Turbulent Gravitational Convection for Maintained and Instantaneous Sources, Proc. Roy. Soc. London, A234, pp. 1-23.

15. Phelps, G. T. and Pond, S., 1971: Spectra of the Temperature and Humidity Fluctuations and of the Fluxes of Moisture and Sensible Heat in the Marine Boundary Layer, J. of the Atmos. Sci., Vol. 28, pp. 918-928.

16. Priestley, C. H. B., and H. K. Ball, 1955: Continuous Convection from an Isolated Source of Heat. Quart. J. Roy. Meteor. Soc., 81, pp. 144-157.

17. Priestley, C. H. B., 1955: Free and Forced Convection in the Atmosphere Near the Ground. Quart J. Roy., Meteor. Soc., Vol. 81, No. 348, pp. 139-143.

18. Priestley, C. H. B., 1959: Turbulent Transfer in the Lower Atmosphere. University of Chicago Press. 130 p.

19. Ryznar, E., 1971: Wind and Temperature Structure in the Surface Layer of the Atmosphere. U. S. Army Research Office - Durham Contract DAGCO 4-67-C-0027.

20. Sheppard, P. A., 1958: Transfer Across the Earth's Surface and Through the Air Above. Quart. J. Roy. Meteor. Soc., 84 (361), pp. 205-224.

21. Stewart, R. H.II, 1970: Laboratory Studies of the Velocity Field Over Deep Water Waves. J. Fluid Mech., 42, pp. 733-754.

22. Stewart, R. W., 1967: Mechanics of the Air-Sea Interface. Physics of Fluids Supplement, 10, SH7-S55.

23. Taylor, R. J., 1958: Thermal Structure in the Lowest Layers of the Atmosphere; Austral. J. Physics. Vol. 11 pp. 168-176.

24. Telford, J. W., 1966: The Convection Mechanism in Clear Air. J. Atmos. Sci., 23, pp. 652-666.

25. Volkov, Y. A., 1969: The Spectra of Velocity and Temperature Fluctuations in Air-Flow Above the Agitated Sea Surface. Izv. Atmospheric and Oceanic Physics. Academy of Sciences, USSR 5(12), Translated by J. Findlay, 723-731.

26. Warner, J., and J. W. Telford, 1967: Convection Below Cloud Base. J. Atmos. Sci., 24, pp. 374-382.

27. Webb, E. K., 1964: Daytime Thermal Fluctuations in the Lower Atmosphere. Appl. Optics., 3(12), pp. 1329-1336.

28. Yefimov, V. V., 1970: On the Structure of the Wind Velocity Field in the Atmospheric Near-Water Layer and the Transfer of Wind Energy to Sea Waves. IZV, Atmospheric and Oceanic Physics, 6, Eng. Trans. JD.L. McIntosh, 1043-1058.

29. Yefimov, V. V., and A. A. Sizov, 1969: Experimental Study of the Field of Wind Velocity over Waves. IZV, Atmospheric and Oceanic Physics, Academy of Sciences, USSR, 5, Eng. Trans. A. Peiperl, 530-537.

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13. ABSTRACT

Temperature, wind (u and w), and wave data observed over Lake Michigan were analyzed to yield results on properties of sensible heat transfer in the near-surface layer. Significant features in the overwater data are associated with positive temperature fluctuations which appear as ramps (micro-thermals) in continuous traces. Objective methods based on the distinctive shape of the ramps were used to identify the occurrences of the micro-thermals. Although micro-thermals accounted for only about ten percent of the total record, they accounted for 32 percent of the total sensible heat flux. Results indicate that the occurrence and maintenance of the micro-thermals, and therefore, enhanced sensible heat flux are related to the presence of the waves. These results were obtained by considering Richardson numbers, significant wave height, and comparisons of wave and temperature traces. The Richardson number criteria for free convection do not appear to be the only determining parameters for the frequency of occurrence nor the development of the observed micro-thermals.

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